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Two-body currents in one-particle one-hole lepton-nucleus interactions within a relativistic mean-field model

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

NuFact 2024 – The 25th International Workshop on Neutrinos from Accelerators

Reference paper

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

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

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9 August 2024

Abstract.

Longitudinal (R_L) and transverse (R_T) responses from inclusive electron scattering from carbon 12 and calcium 40 nuclei are computed within a fully relativistic and unfactorized model for the initial and final states, and one- and two-body current operators leading to the one-particle one-hole responses. We find that the two-body contributions have no effect on R_L but they increase R_T by up to 30%, depending on the energy and momentum transfer. Inclusive cross sections have also been computed. In this case, the increase of R_T due to two-body currents will translate into an increase in the cross-sections depending on the degree of transversity of each kinematic.

The comparison with carbon data is good for the responses and the cross sections. In the case of calcium, while the model compares well with the cross section data, the agreement with the responses is generally poor. However, the inconsistencies between different data sets for the separate responses in this nucleus points to uncertainties underlying the procedure to extract the responses that are not considered (or largely underestimated) in the experimental error bars.

Our calculation is fully relativistic and considers within the full quantum mechanical description both the initial and final nucleon states involved in the process. We also show that it is essential to go beyond the plane-wave approach, since incorporating the distortion of the nucleons while making the initial and final states orthogonal, allows to reproduce both the shape and magnitude of the cross section data and carbon responses. The good agreement with the electron scattering experimental data supports the use of this approach to describe the analogous neutrino-induced scattering reaction.

Keywords: meson-exchange currents, nuclear responses, electron-nucleus scattering, relativistic mean-field, quasielastic scattering

arXiv:2203.09996

PHYSICAL REVIEW C **108**, 064608 (2023)

Editors' Suggestion

Relativistic two-body currents for one-nucleon knockout in electron-nucleus scattering

T. Franco-Munoz,[1] J. García-Marcos,[1,2] R. González-Jiménez,[1] and J. M. Udías[1]

[1]*Grupo de Física Nuclear, Departamento de Estructura de la Materia, Física Térmica y Electrónica, Facultad de Ciencias Físicas, Universidad Complutense de Madrid and IPARCOS, CEI Moncloa, Madrid 28040, Spain*

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We present a detailed study of the contribution from two-body currents to the one-nucleon knockout process induced by electromagnetic interaction. The framework is a relativistic mean-field model in which bound and scattering nucleons are consistently described as solutions of Dirac equation with potentials. We show results obtained with the most general expression of the two-body operator, in which the intermediate nucleons are described by relativistic mean-field bound states; then, we propose two approximations consisting in describing the intermediate states as nucleons in a relativistic Fermi gas, preserving the complexity and consistency in the initial and final states. These approximations simplify the calculations considerably, allowing us to provide outcomes in a reasonable computational time. The results obtained under these approximations are validated by comparing with those from the full model. Additionally, the theoretical predictions are compared with experimental data of the longitudinal and transverse responses of carbon 12. The agreement with data is outstanding for the longitudinal response, where the contribution from the two-body operator is negligible. In the transverse sector, the two-body current increases the response from 30 to 15 %, depending on the approximations and kinematics, in general, improving the agreement with data.

PhysRevC.108.064608

Outline

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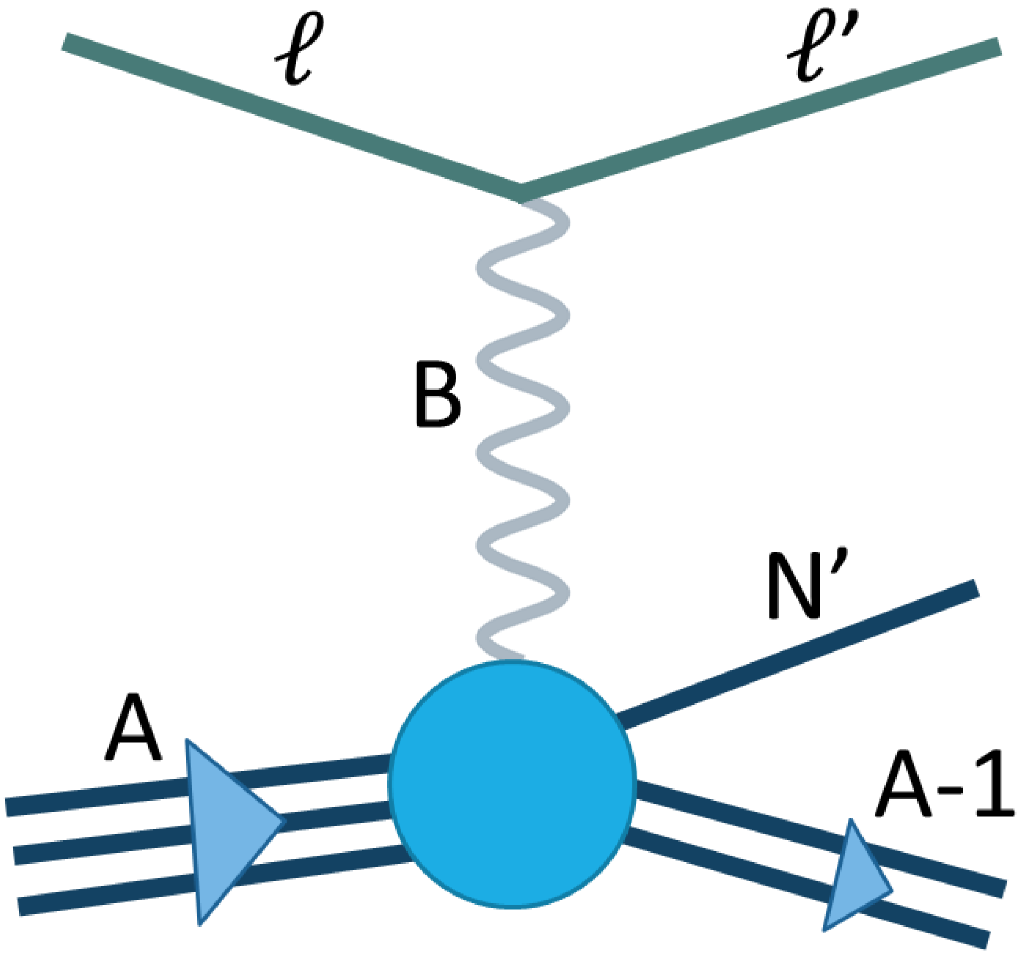
- **Theoretical framework**
  - Independent Particle Shell Model
  - Hadronic current: RMF and FSI
  - Two-body **meson-exchange currents** in particle-hole excitations
- **Electron-nucleus scattering**
  - ^{12}C inclusive responses and cross section
  - ^{40}Ca inclusive cross section
- **Neutrino-nucleus scattering**
  - ^{12}C inclusive cross section
- Conclusions and future prospects

Outline

- **Theoretical framework**

Quasielastic scattering

- The lepton is scattered by a single nucleon that is consequently ejected from the target nucleus.

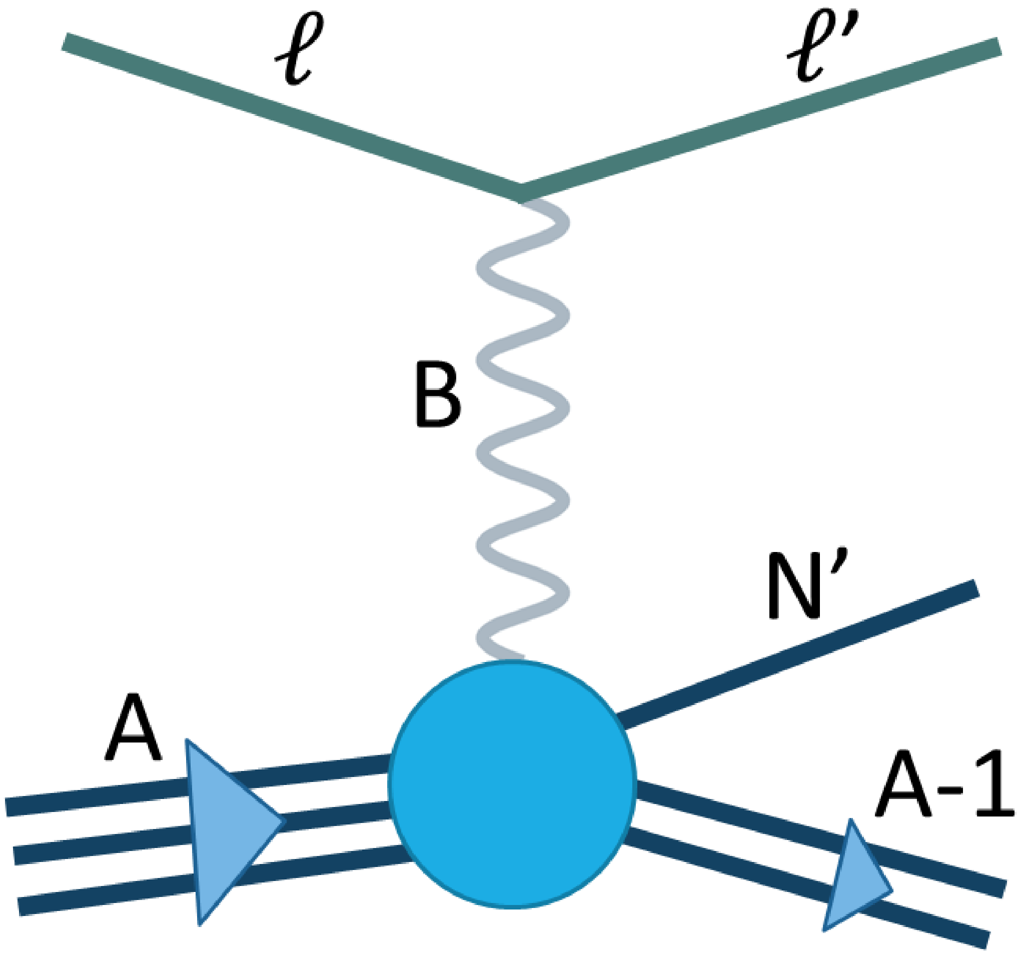


Quasielastic scattering

- The lepton is scattered by a single nucleon that is consequently ejected from the target nucleus.

- The cross section is proportional to the contraction of leptonic and hadronic tensors:

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



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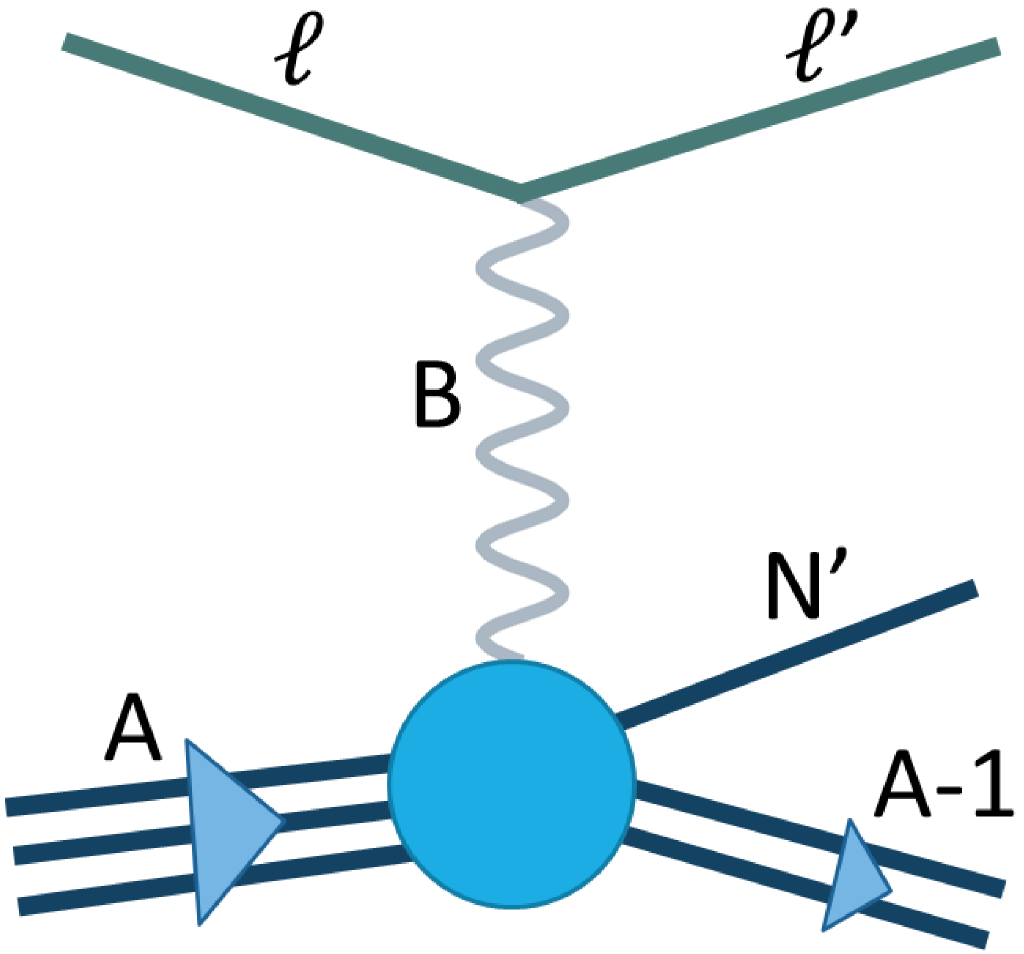
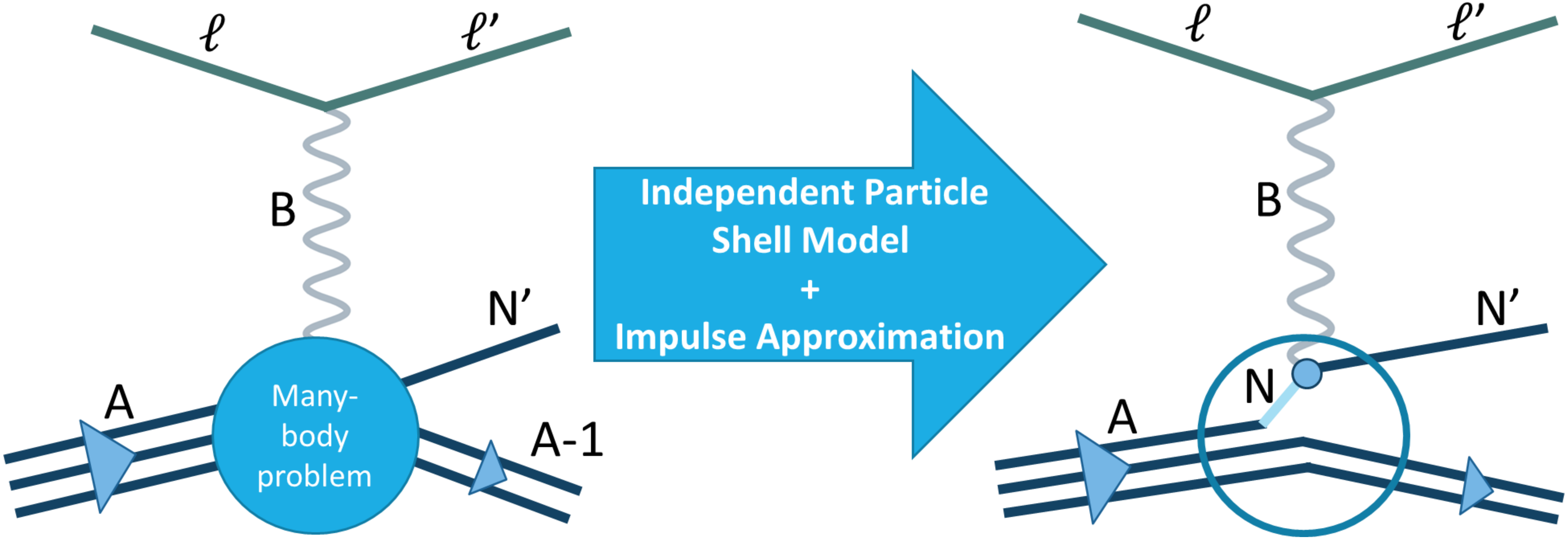
- The hadronic tensor contains all the information of the boson-nucleus interaction and all hadronic final-state interactions.

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



Quasielastic scattering



$$J^{\mu}_{had} = \langle N', A-1 | \Gamma^{\mu}_{many-body} | A \rangle$$

$$J^{\mu}_{had} = \int d\boldsymbol{p}\, \bar{\Psi}^{s}(\boldsymbol{p}'_N, \boldsymbol{p}_N) \Gamma^{\mu}_{1b}\, \Psi^{\kappa}_{m_j}(\boldsymbol{p})$$

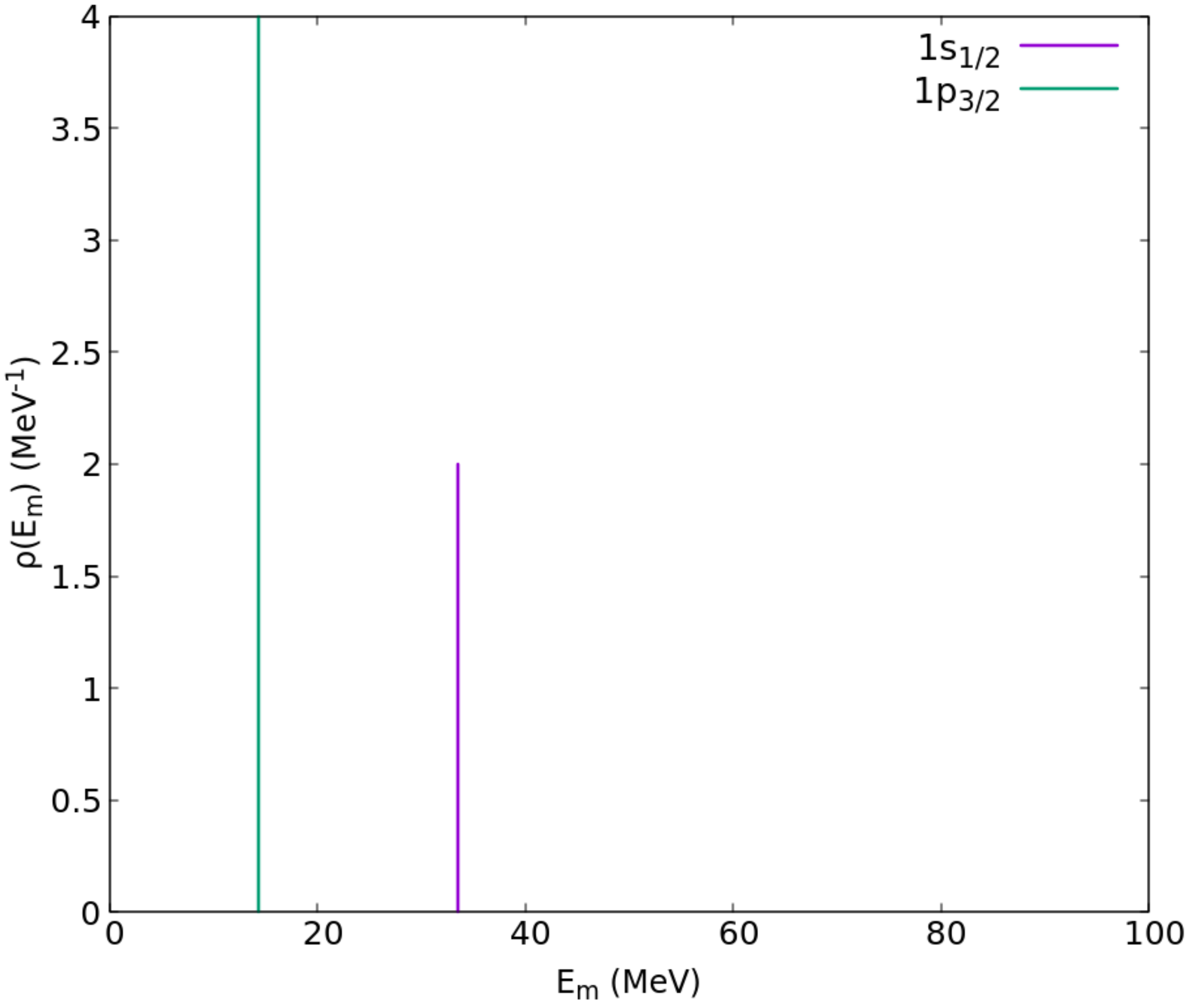
Outline

- Theoretical framework
    - **Independent Particle Shell Model**

^{12}C independent particle shell model

- **^{12}C** pure shell model:
  - **Occupations**
    - 2 nucleons in $1s_{1/2}$
    - 4 nucleons in $1p_{3/2}$
  - **Missing energy distribution**

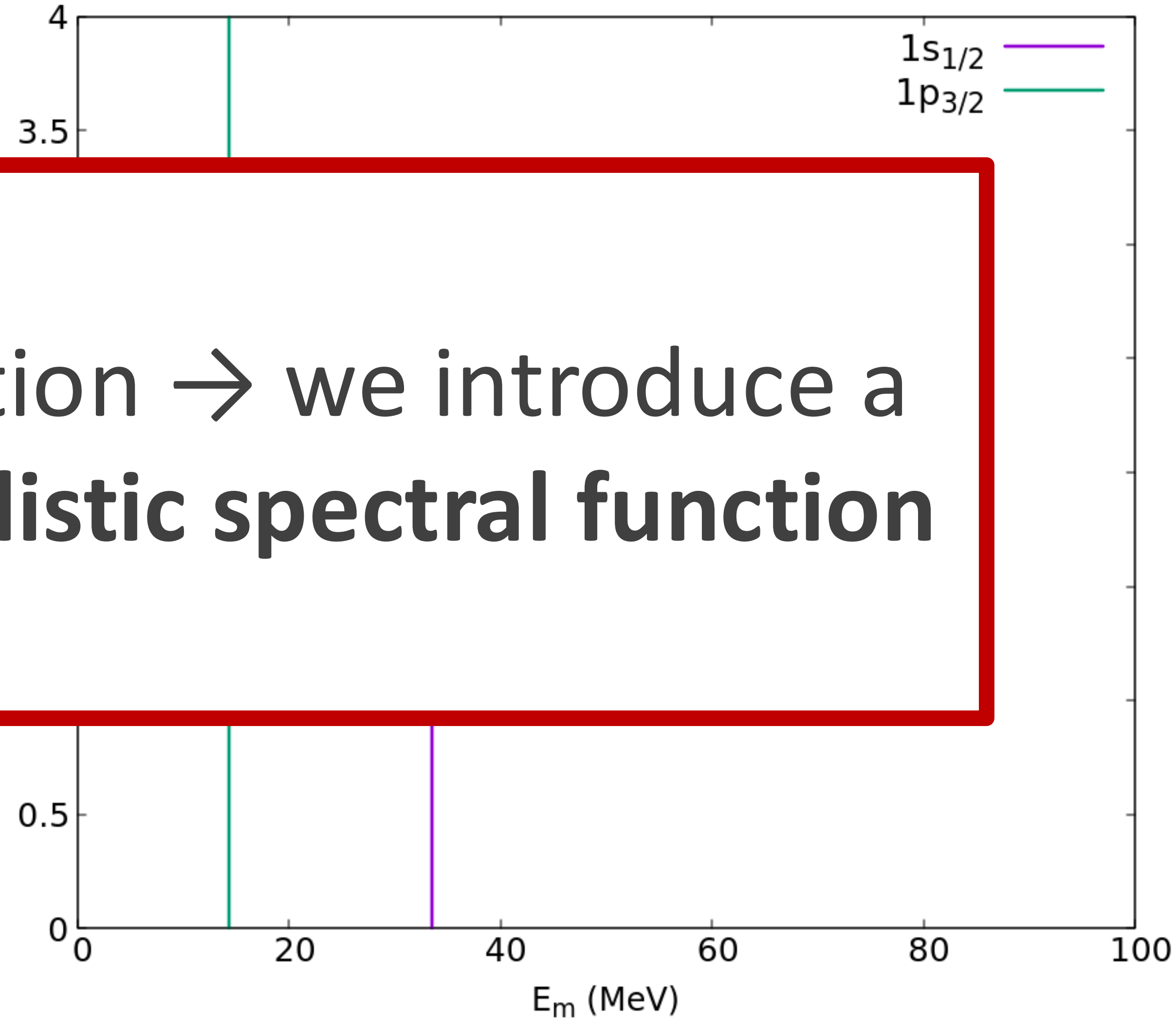
$$\rho(E_m) = \sum_{\kappa} N_\kappa \, \delta(E_m - E_{m,\kappa})$$



^{12}C independent particle shell model

- **^{12}C** pure shell model:
  - **O**
  - **M**

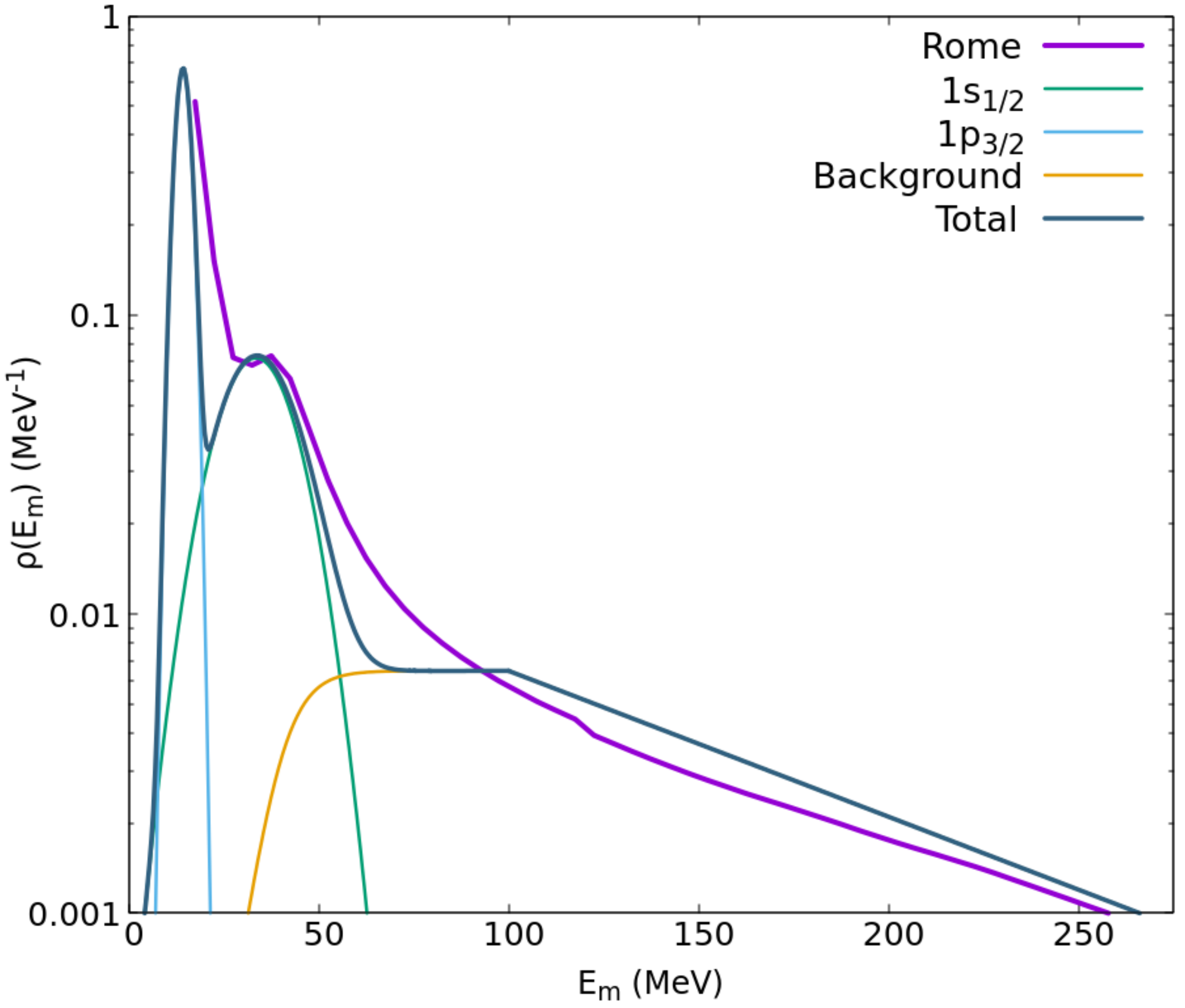
$$\rho(E_m) = \sum_{\kappa} N_\kappa \, \delta(E_m - E_{m,\kappa})$$



Simplistic approximation → we introduce a model based on a **realistic spectral function**

^{12}C independent particle shell model

- Nuclear structure based on a realistic spectral function:
  - **Reduced shell model occupations**
    - 1.8 nucleons in $1s_{1/2}$
    - 3.3 nucleons in $1p_{3/2}$



Rome Spectral Function: O. Benhar et al., Nuclear Physics A 579, 493 (1994).

^{12}C independent particle shell model

- Nuclear structure based on a realistic spectral function:
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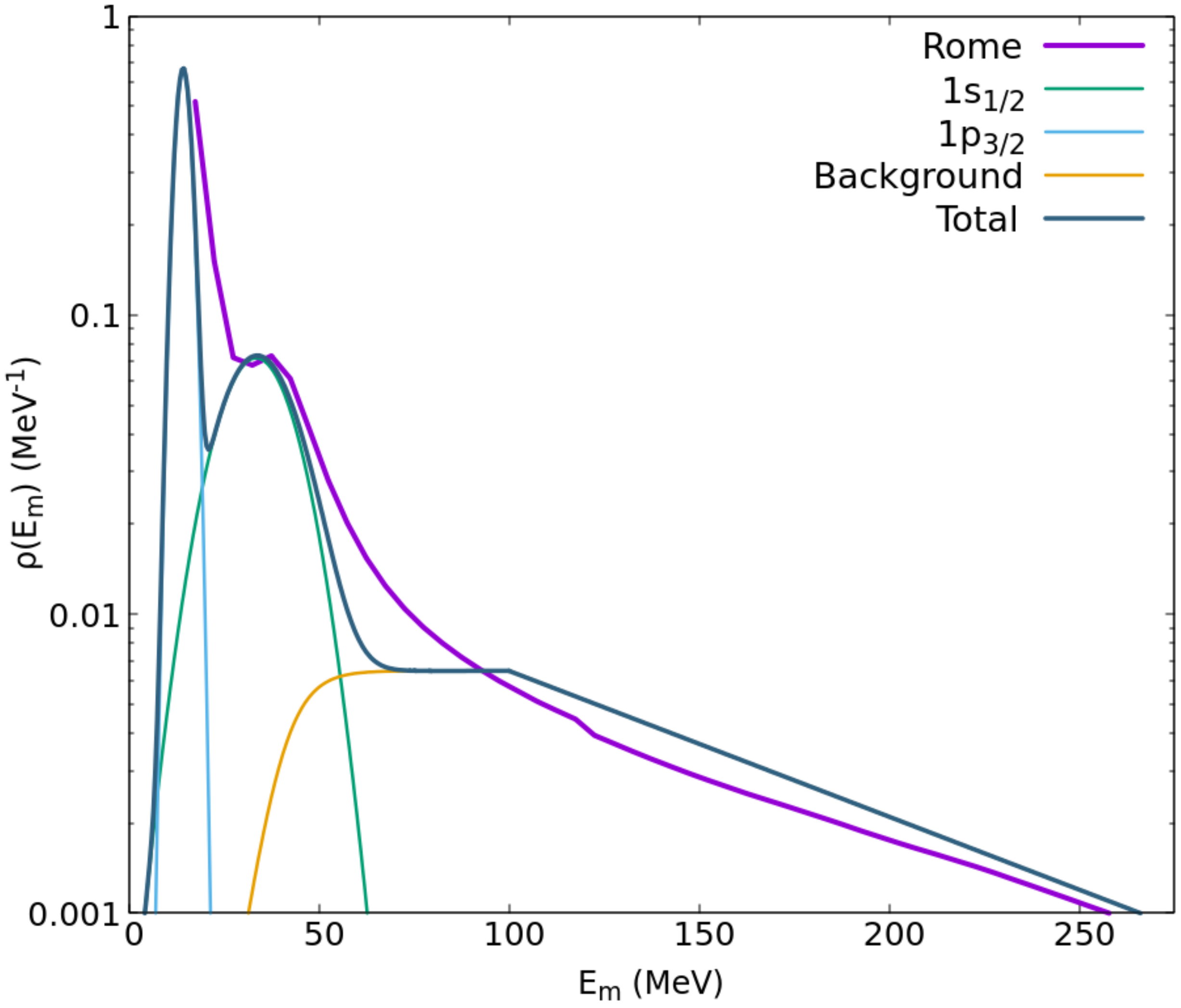
    - 3.3 nucleons in $1p_{3/2}$
  - **Continuous missing energy profile**



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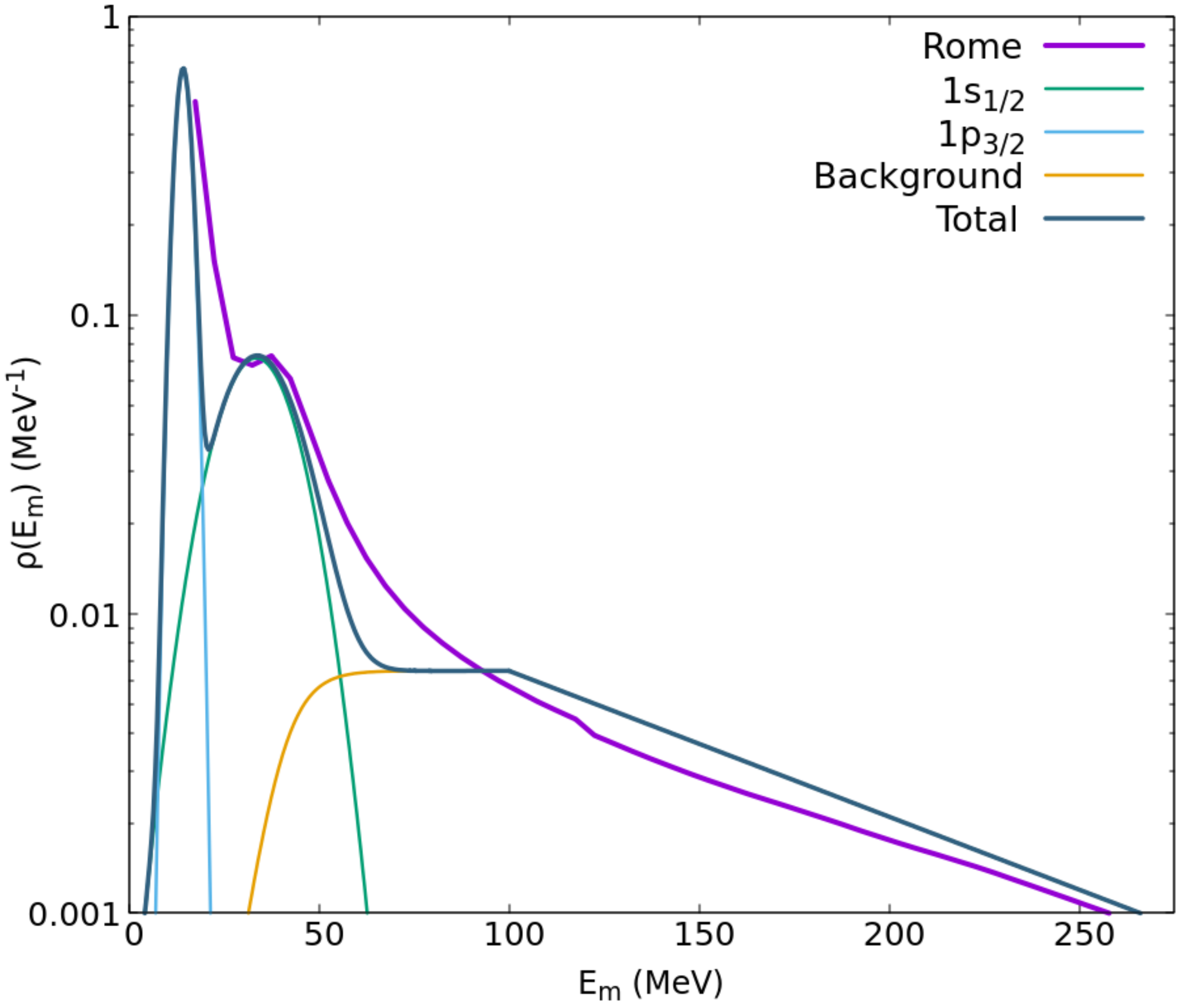
  - Continuous missing energy profile
  - **Background due to short range correlations**
    - 0.9 nucleons



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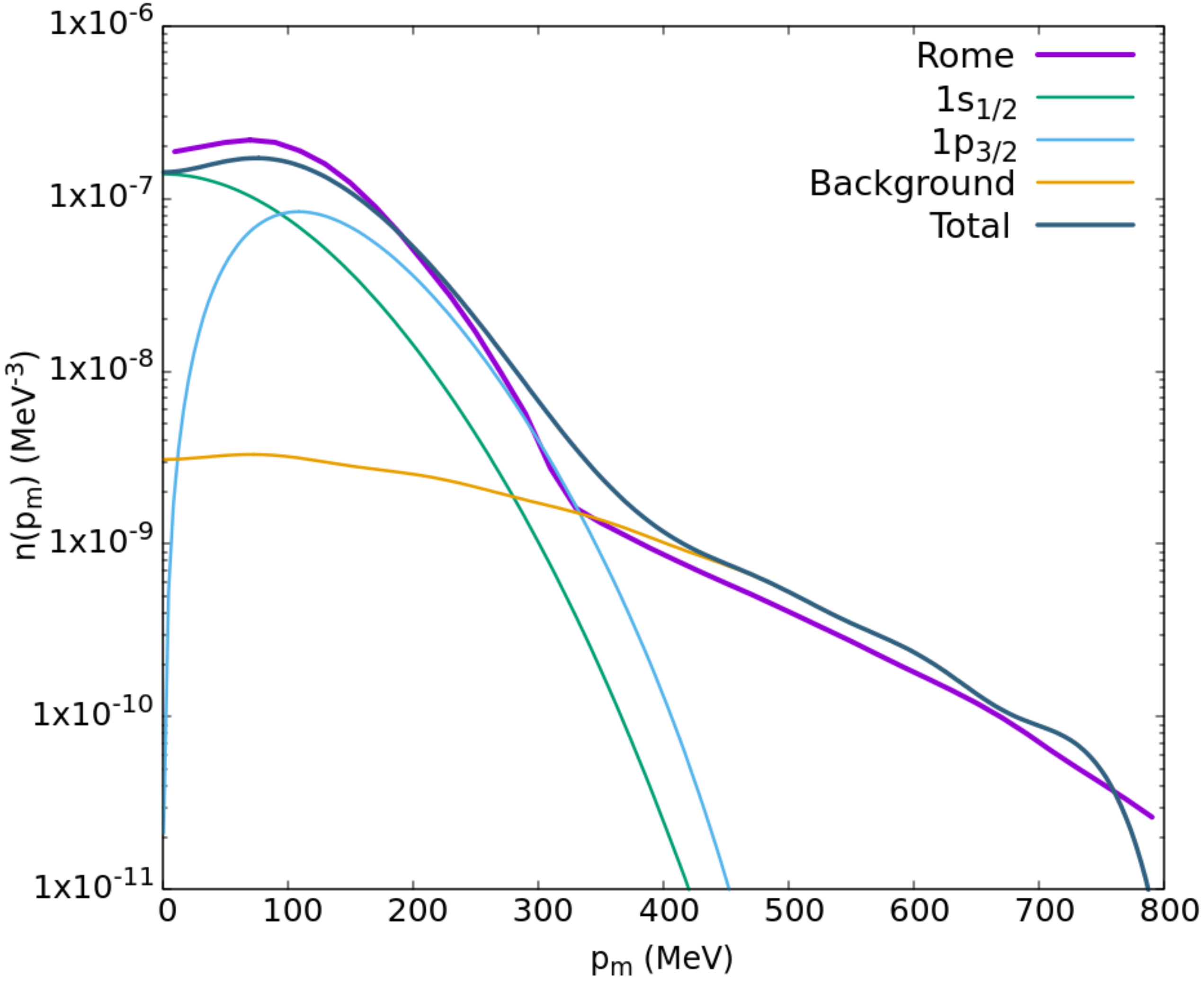


Rome Spectral Function: O. Benhar et al., Nuclear Physics A 579, 493 (1994).

Outline

- Theoretical framework
  - Independent Particle Shell Model
  - **Hadronic current: RMF and FSI**

Hadronic current

- The hadronic current contains all the information of the boson-nucleus interaction and all hadronic final-state interactions.

$$J^{\mu}_{had} \sim \overline{\Psi}^{s}(\boldsymbol{p}'_N, \boldsymbol{p}_N)\, \Gamma^{\mu} \;\; \Psi^{\kappa}_{m_j}(\boldsymbol{p})$$

Hadronic current operator

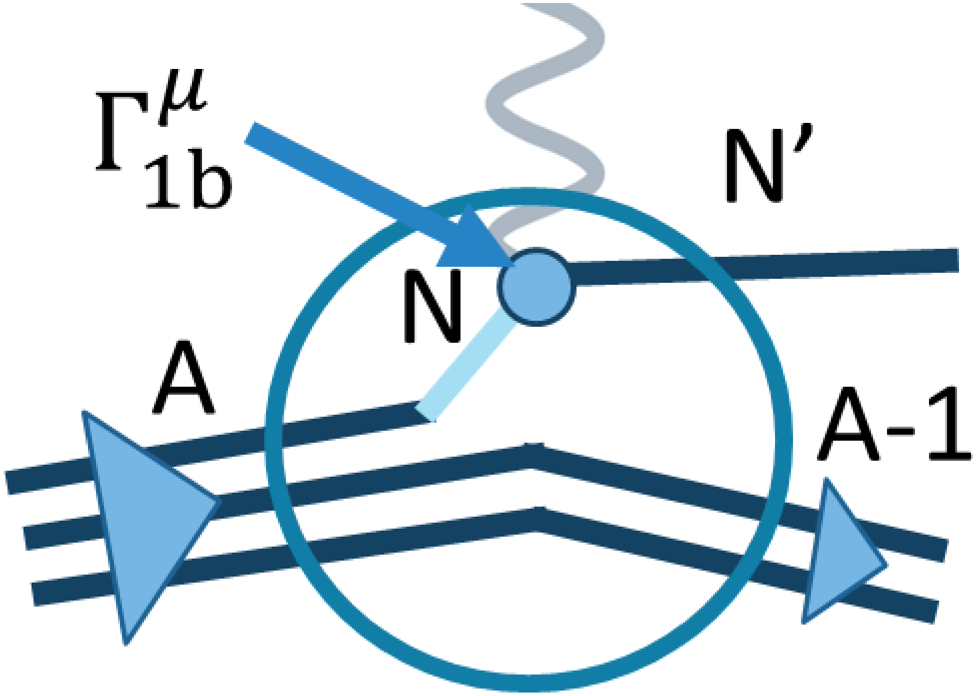
$$J^{\mu}_{had} \sim \overline{\Psi}^{s}(\boldsymbol{p}'_N, \boldsymbol{p}_N)\, \Gamma^{\mu}\, \Psi^{\kappa}_{m_j}(\boldsymbol{p})$$

- **Hadronic current operator**: includes all the processes that lead to a final 1p-1h state.

Hadronic current operator

$$J^{\mu}_{had} \sim \overline{\Psi}^{s}(\boldsymbol{p}'_N, \boldsymbol{p}_N)\, \Gamma^{\mu}_{1b}\, \Psi^{\kappa}_{m_j}(\boldsymbol{p})$$

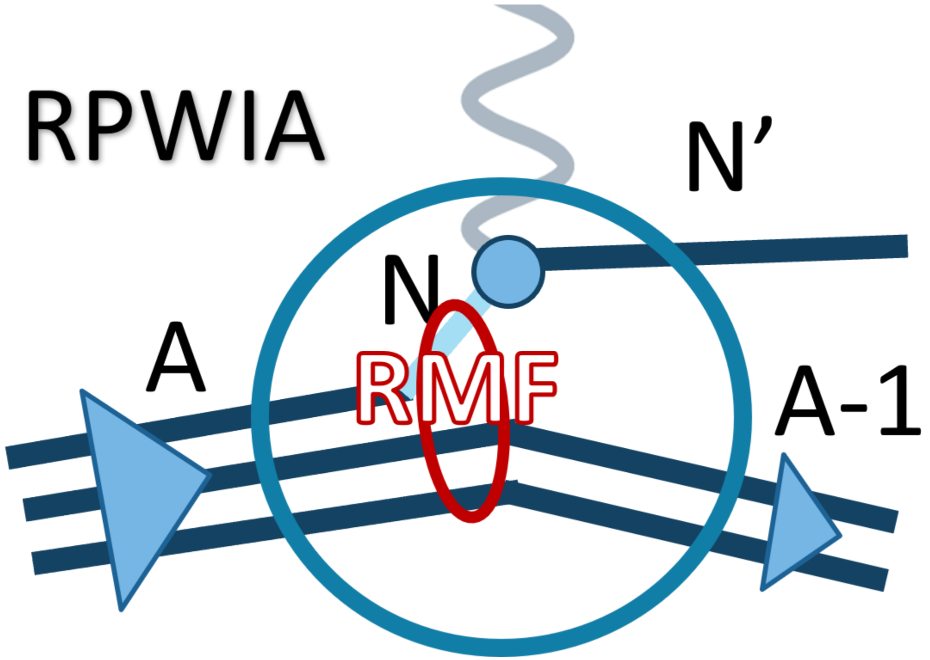
- **Hadronic current operator**: includes all the processes that lead to a final 1p-1h state.
- In the **impulse approximation**, it corresponds to the **1-body** current operator.



Initial bound nucleon

$$J^{\mu}_{had} \sim \overline{\Psi}^{s}(\boldsymbol{p}'_N, \boldsymbol{p}_N)\, \Gamma^{\mu}_{1\mathrm{b}}\, \Psi^{\kappa}_{m_j}(\boldsymbol{p})$$

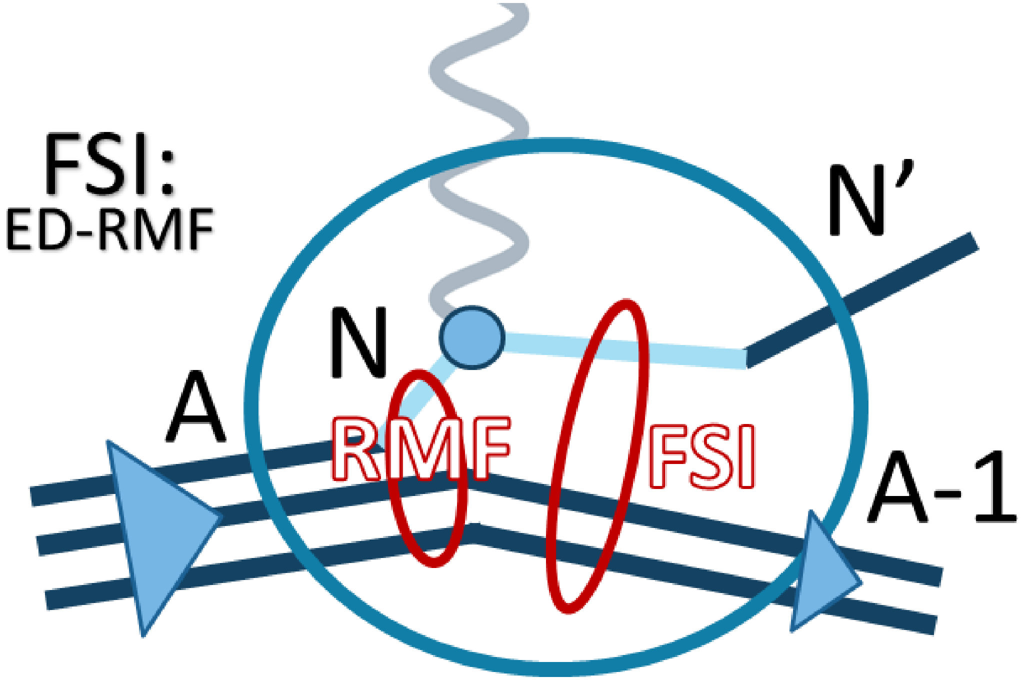
- **Initial nucleon**: bound wave function within the relativistic mean-field (RMF) model.



Knocked out nucleon

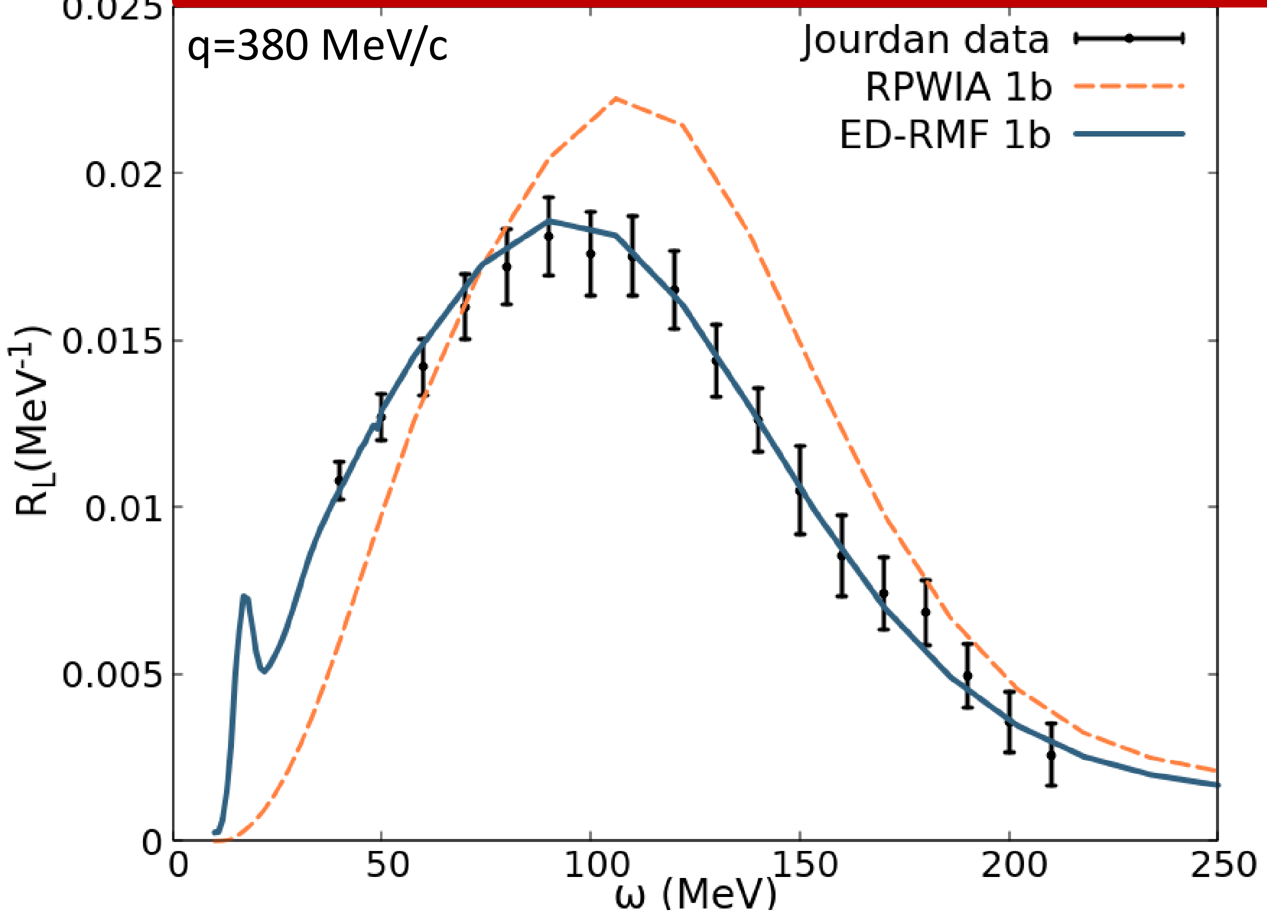
$$J^{\mu}_{had} \sim \bar{\Psi}^{s}(\boldsymbol{p}'_N, \boldsymbol{p}_N)\, \Gamma^{\mu}_{1b}\, \Psi^{\kappa}_{m_j}(\boldsymbol{p})$$

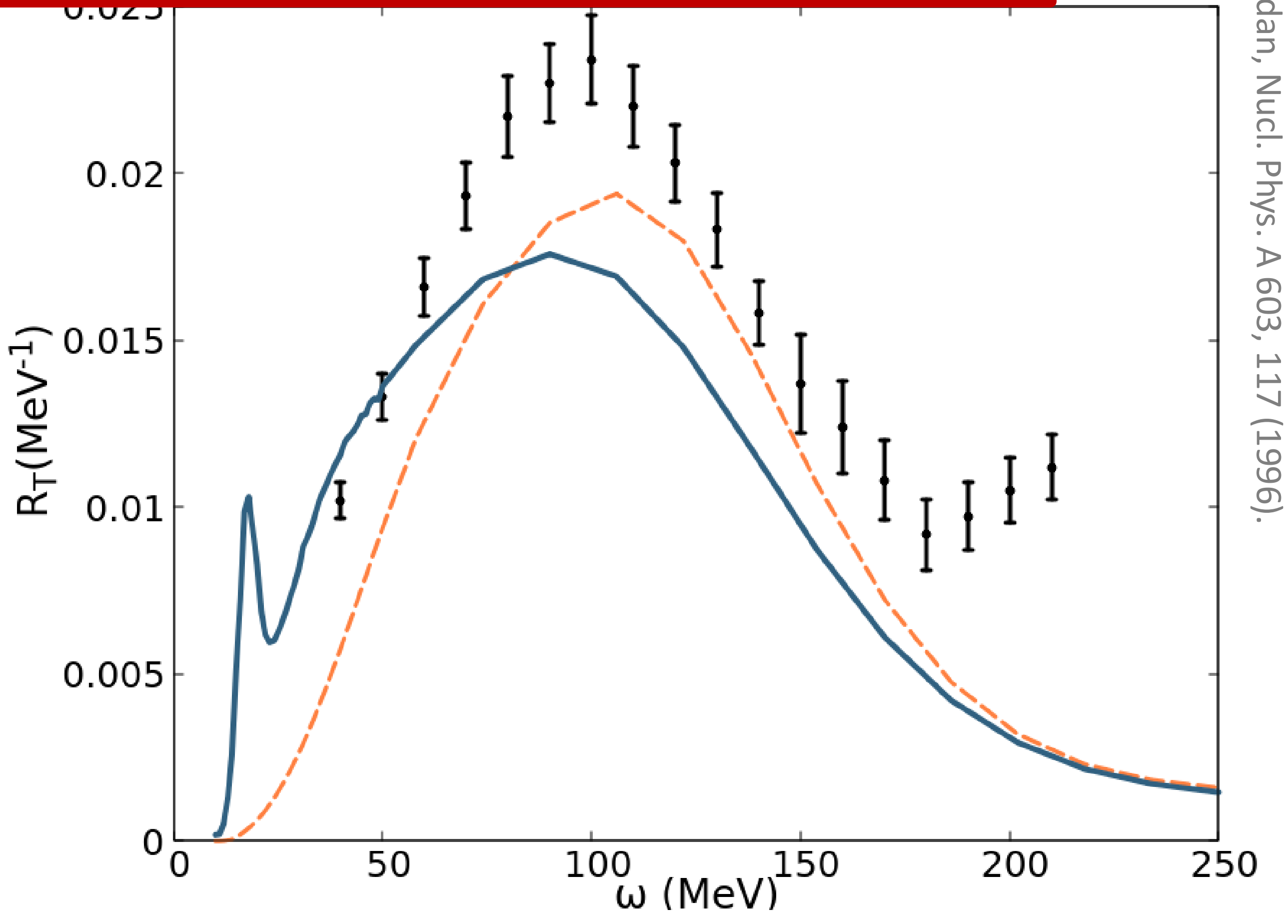
- **Knocked out nucleon**: distorted wave function computed as a solution of the Dirac equation in the continuous with the energy dependent relativistic mean-field (ED-RMF) potential.



^{12}C electromagnectic inclusive responses

Distortion of the outgoing nucleon (FSI) and orthogonality between initial and final states are **important** to **describe the data**





J. Jourdan, Nucl. Phys. A 603, 117 (1996).

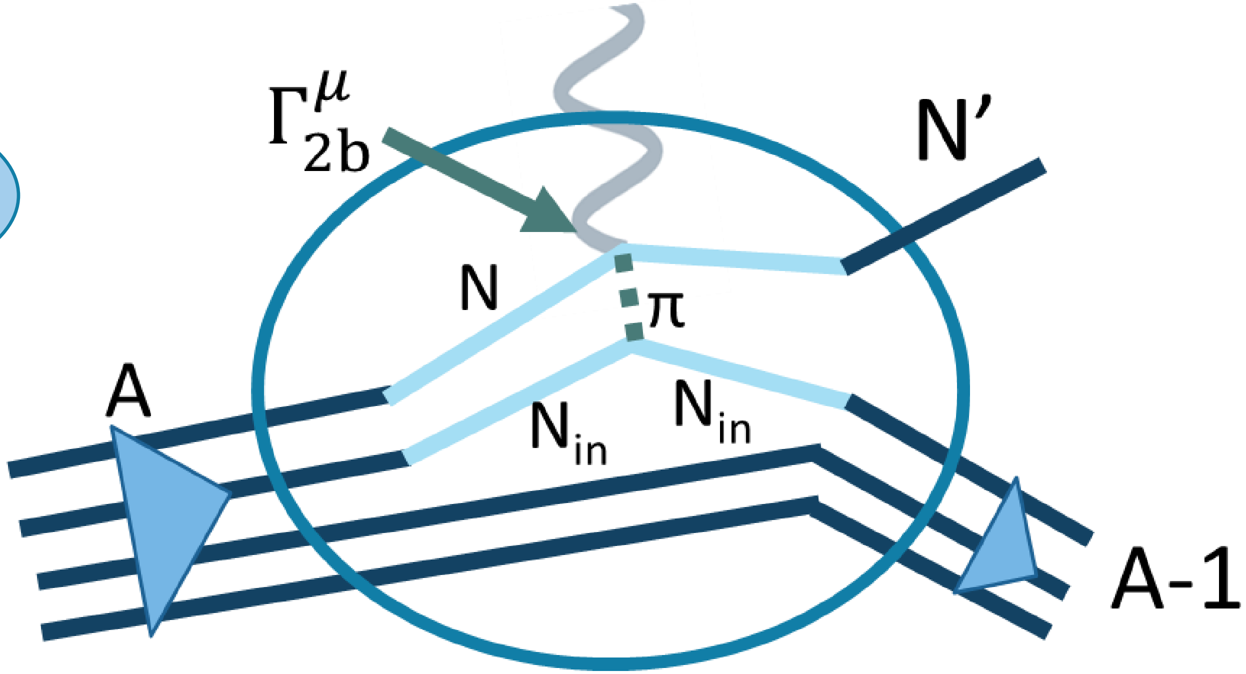
Outline

- Theoretical framework
  - Independent Particle Shell Model
  - Hadronic current: RMF and FSI
  - **Two-body meson-exchange currents in particle-hole excitations**

Meson exchange currents

- We include **one-pion exchange effects** by incorporating **two-body meson-exchange currents** with a final paticle-hole state.

$$J^{\mu}_{had} = J^{\mu}_{had,1b} + J^{\mu}_{had,2b}$$



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- We include **one-pion exchange effects** by incorporating **two-body meson-exchange currents** with a final paticle-hole state.

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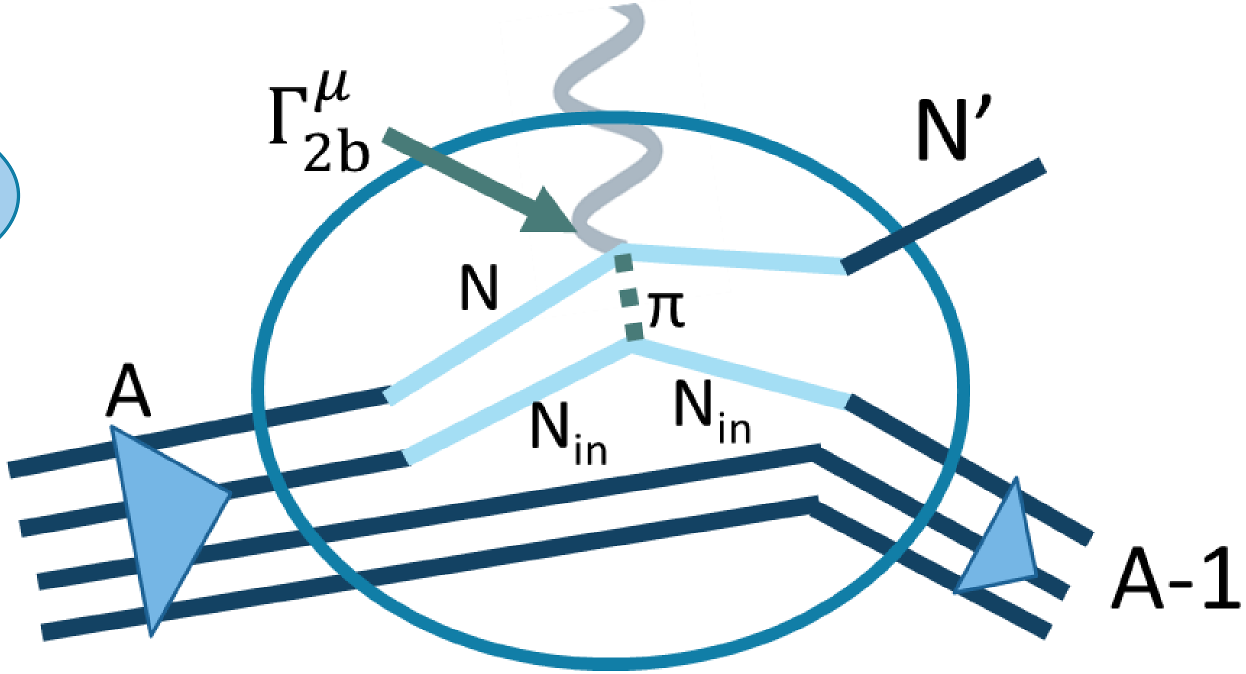
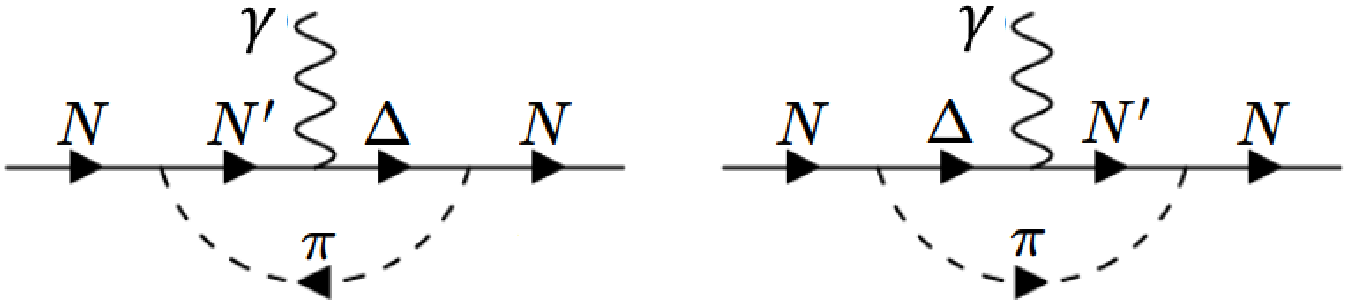
- The **1p-1h excitation** occurs when one of the outgoing nucleons of the two-particle two-hole interaction remains bound to the nucleus.

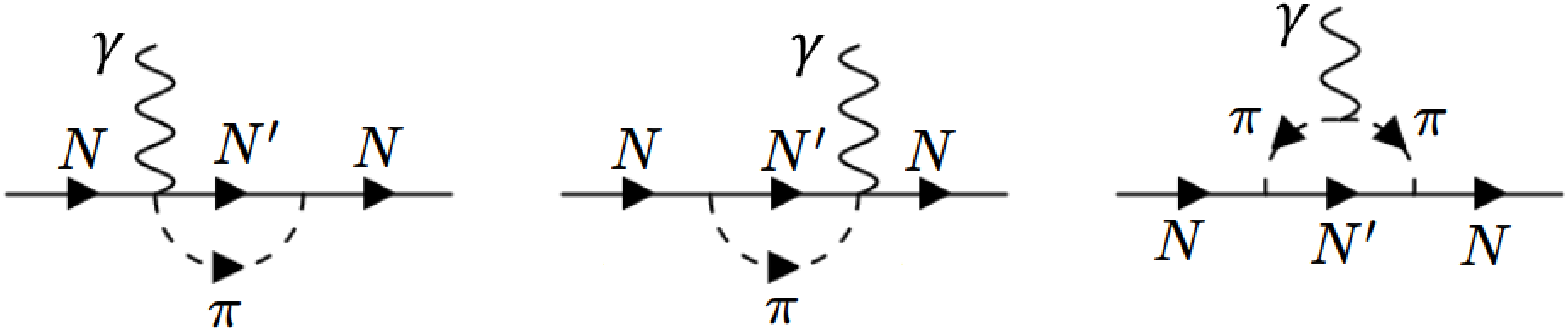


Meson exchange currents

- MEC contributions in **electron-nucleus** interaction
  - Delta resonance mechanism

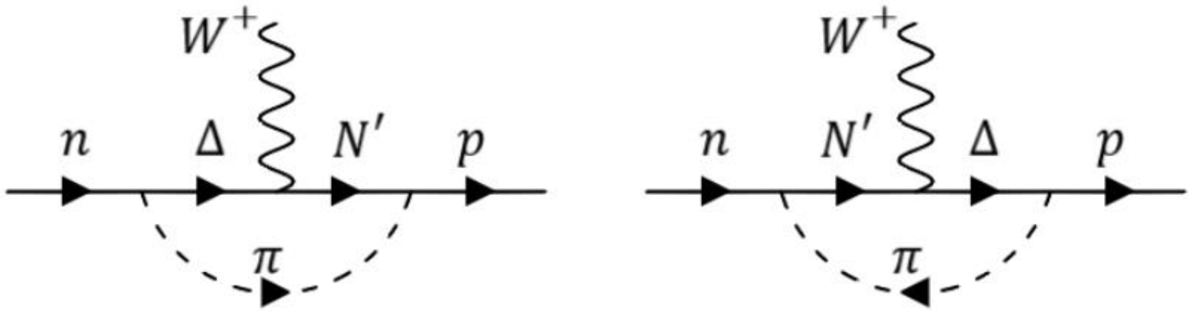


  - ChPT background

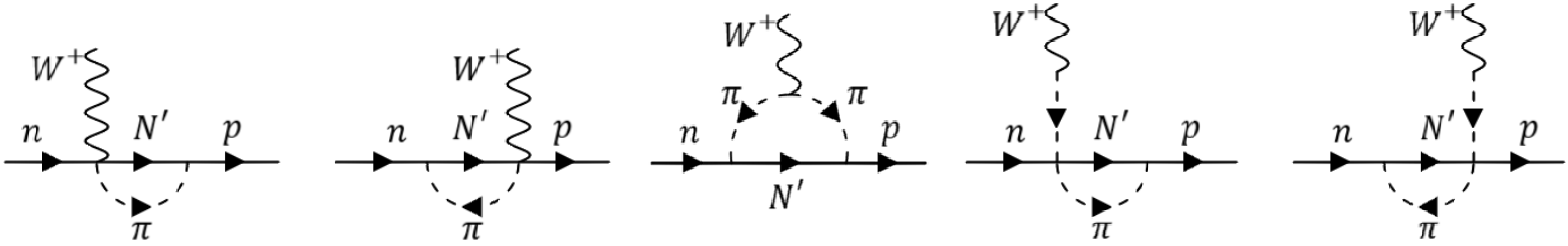


Meson exchange currents

- MEC contributions in **neutrino-nucleus** interaction
  - Delta resonance mechanism



  - ChPT background



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- **Electron-nucleus scattering**

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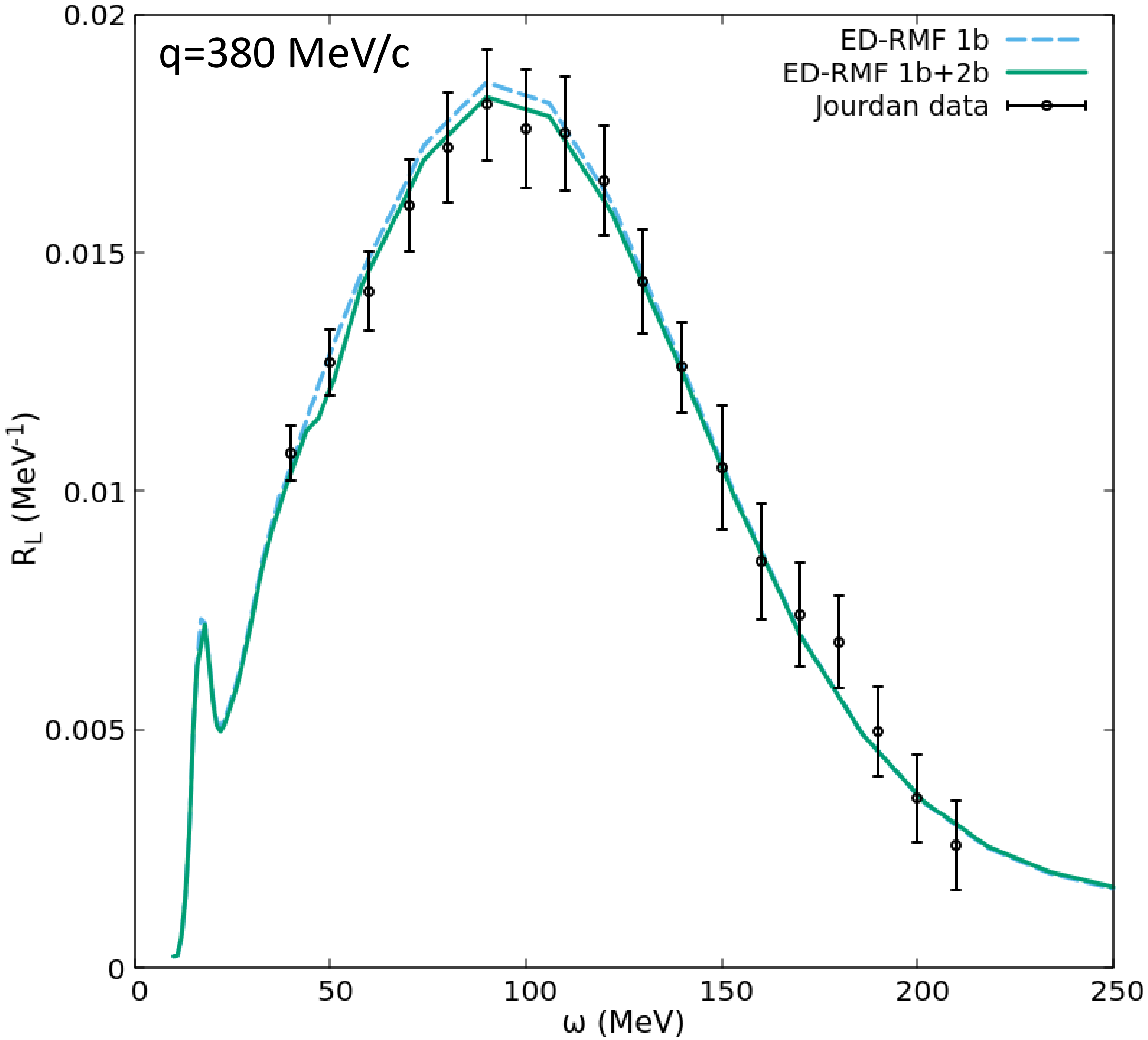
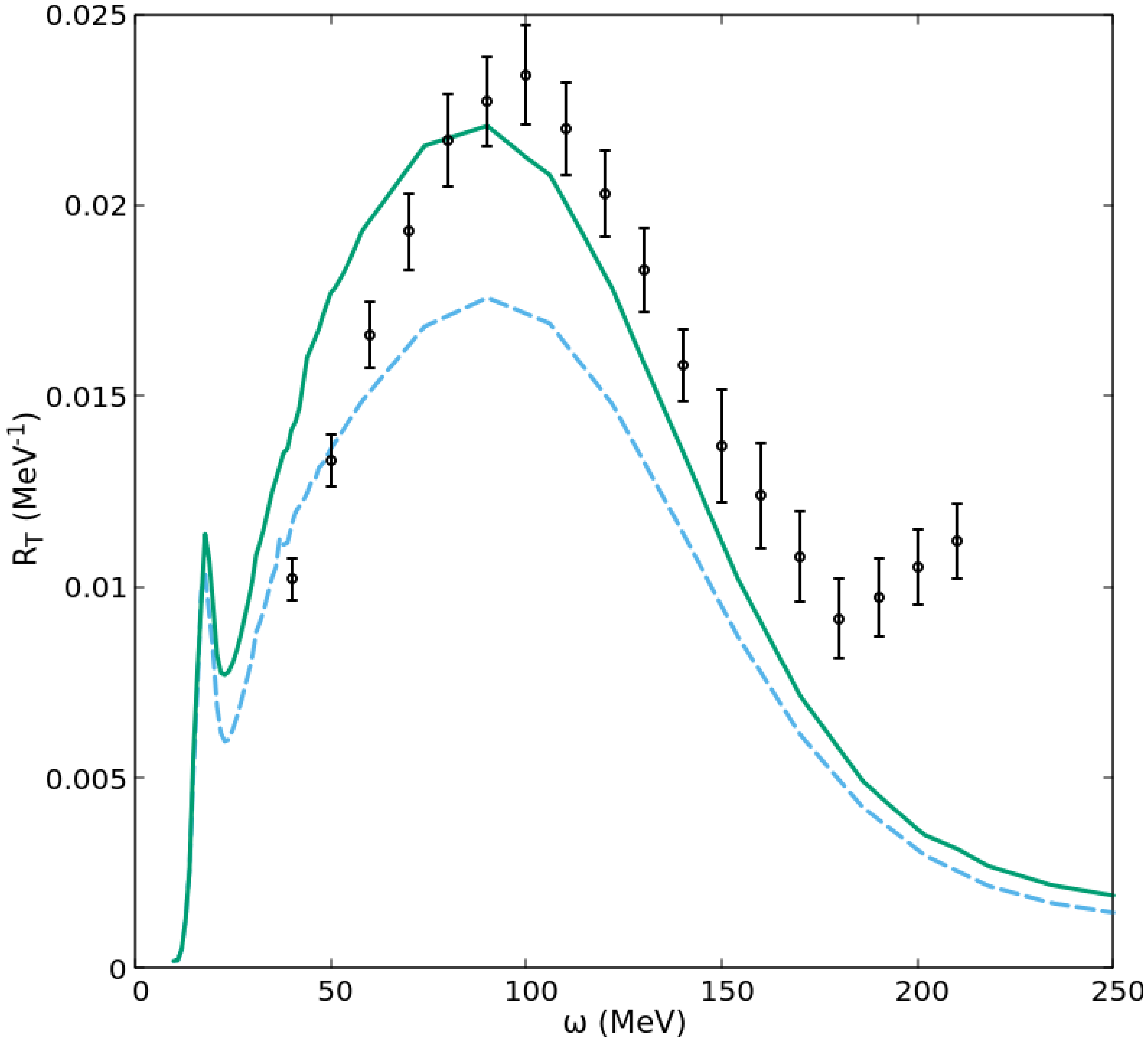
  - **^{12}C inclusive responses and cross section**

^{12}C electromagnetic inclusive responses





J. Jourdan, Nucl. Phys. A 603, 117 (1996).

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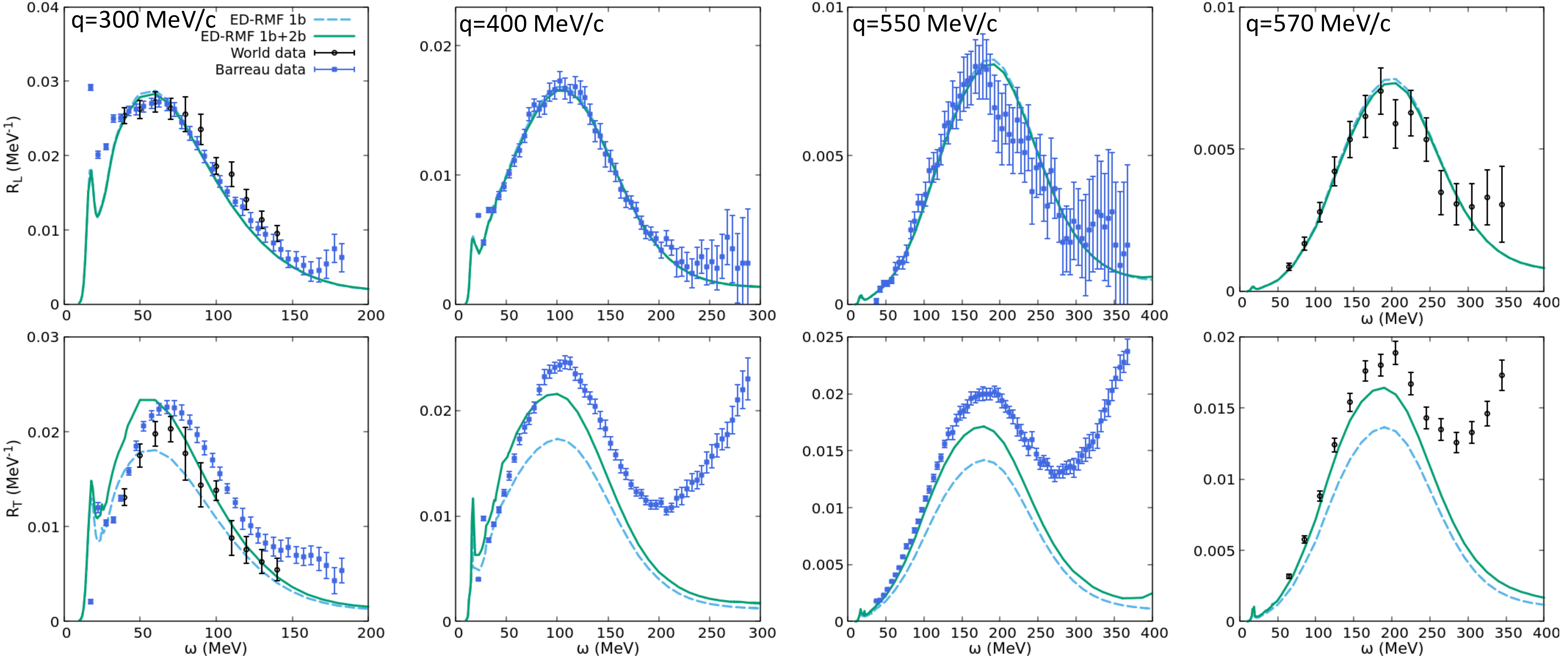

J. Jourdan, Nucl. Phys. A 603, 117 (1996). P. Barreau et al., Nuclear Physics A 402,515 (1983).

^{12}C electromagnetic inclusive cross section

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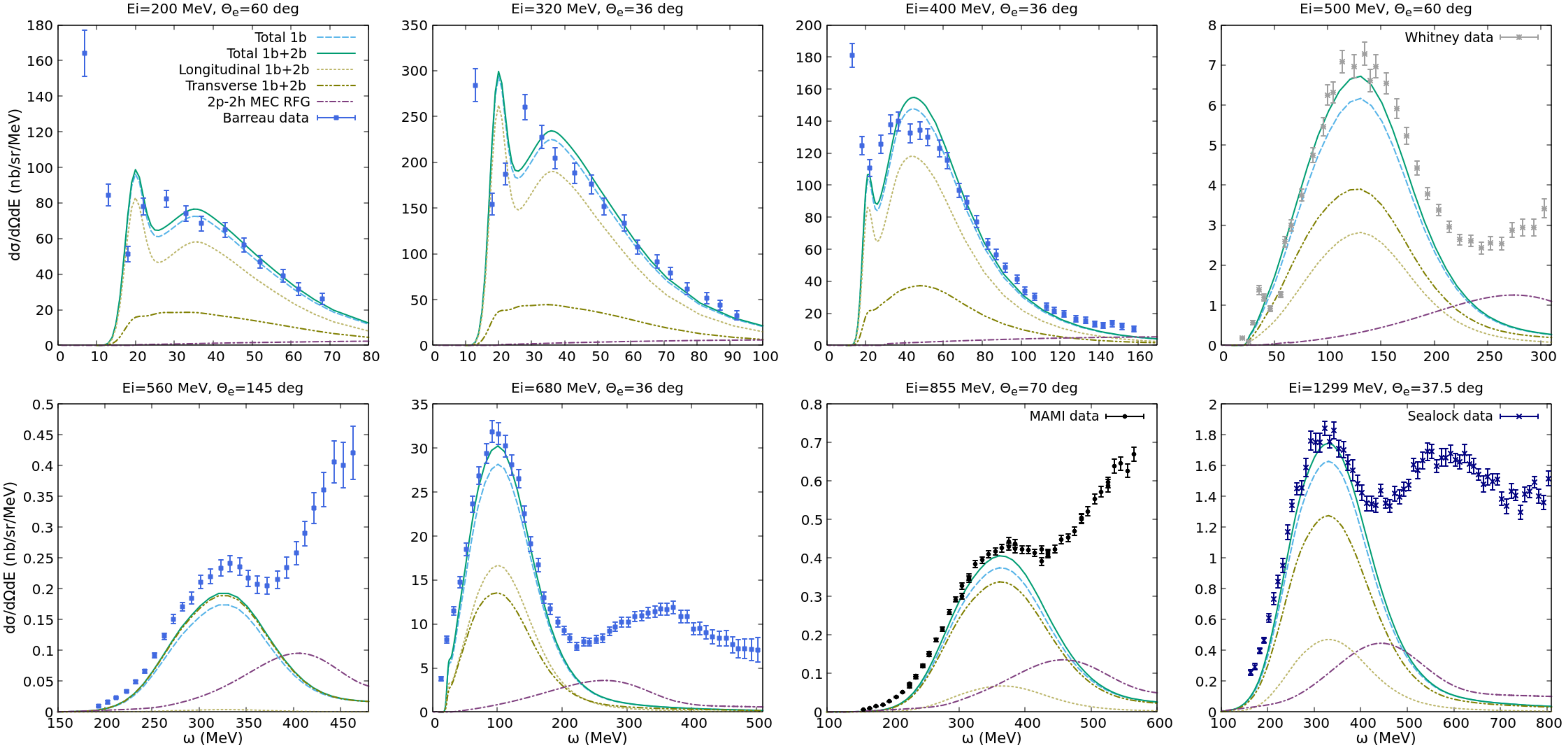

Data: https://discovery.phys.virginia.edu/research/groups/qes-archive/data/12C.html

M. Mihovilovičet al., Few-Body Syst 65, 78 (2024)

Outline

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  - Two-body meson-exchange currents in particle-hole excitations
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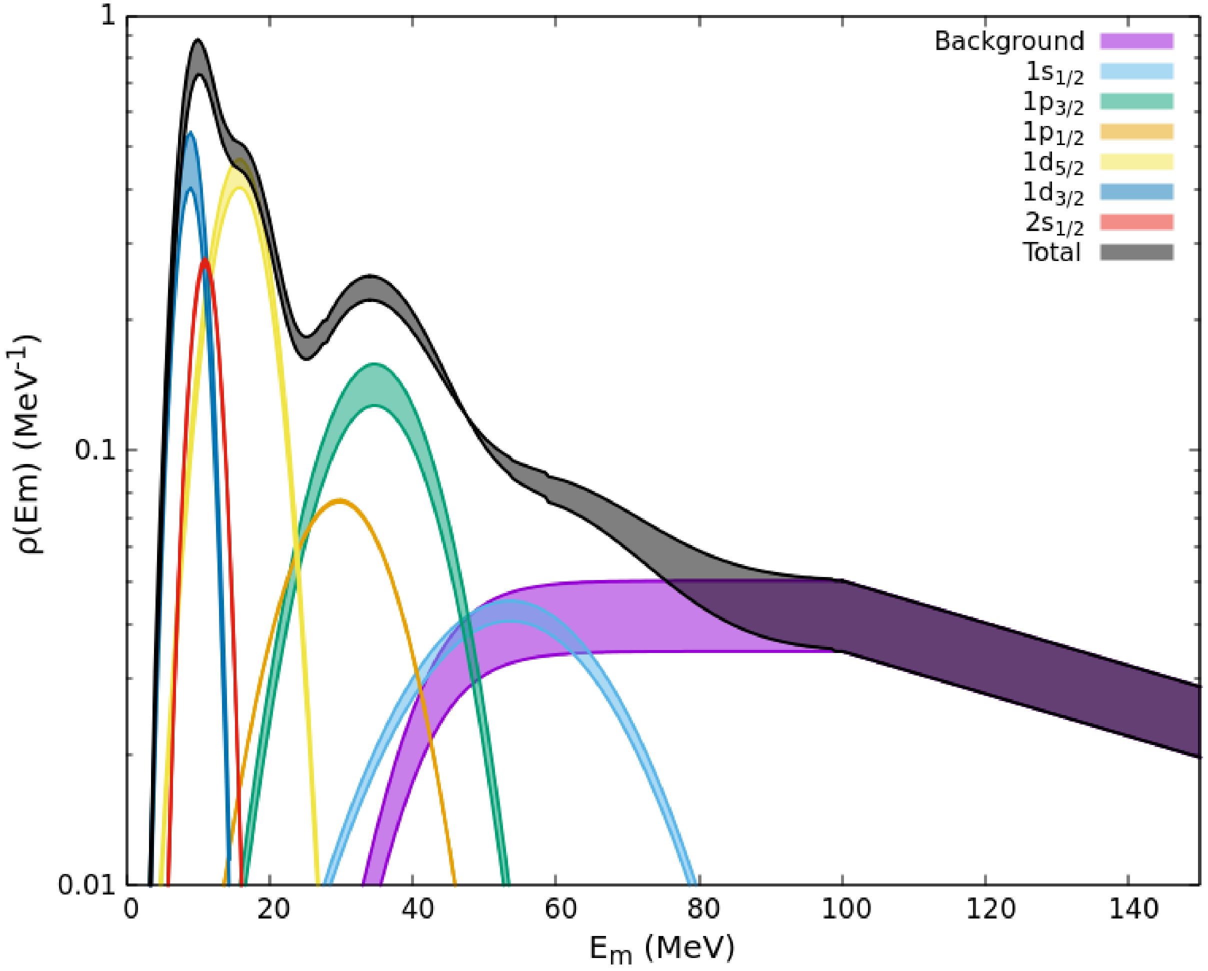
  - ^{12}C inclusive responses and cross section
  - **^{40}Ca inclusive cross section**

^{40}Ca independent particle shell model

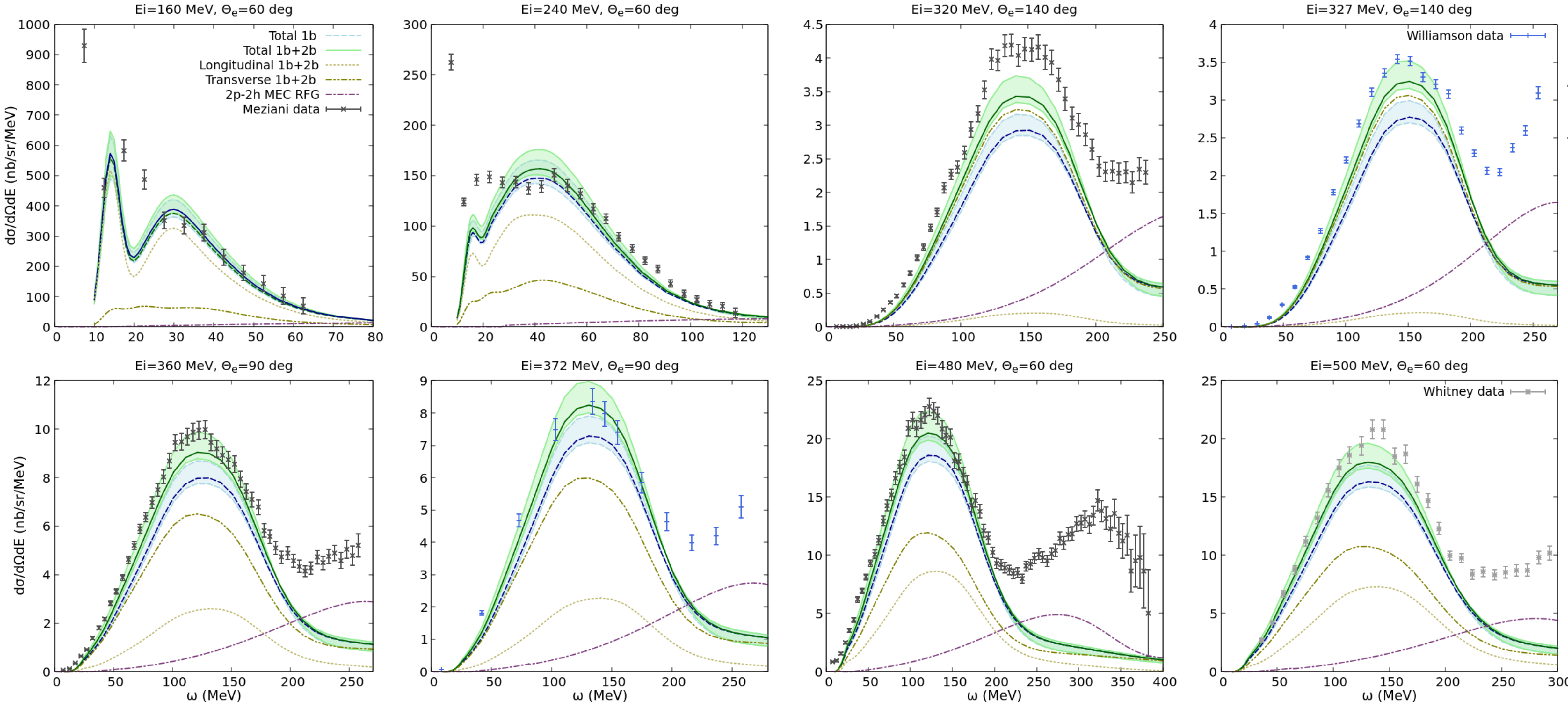
- *Realistic* treatment of nuclear structure:
  - Reduced shell model occupations

Shell model state	Occupation probability
$1d_{3/2}$	0.5 – 0.7
$2s_{1/2}$	0.5 – 0.7
$1d_{5/2}$	0.6 – 0.8
$1p_{3/2}+1p_{1/2}$	0.6 – 0.8
$1s_{1/2}$	0.7 – 0.85

  - Continuous missing energy profile
  - Background due to short range correlations



^{40}Ca electromagnetic inclusive cross section



Data: discovery.phys.virginia.edu/research/groups/qes-archive/data/40Ca.html

Outline

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  - ^{12}C inclusive responses and cross section
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- **Neutrino-nucleus scattering**

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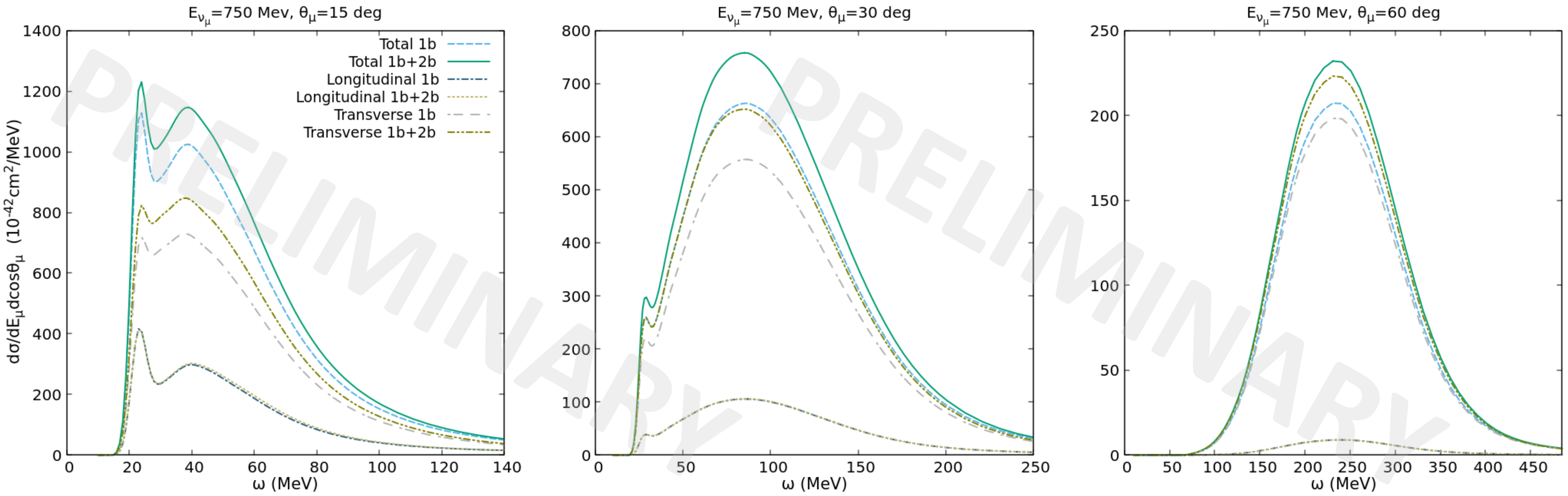
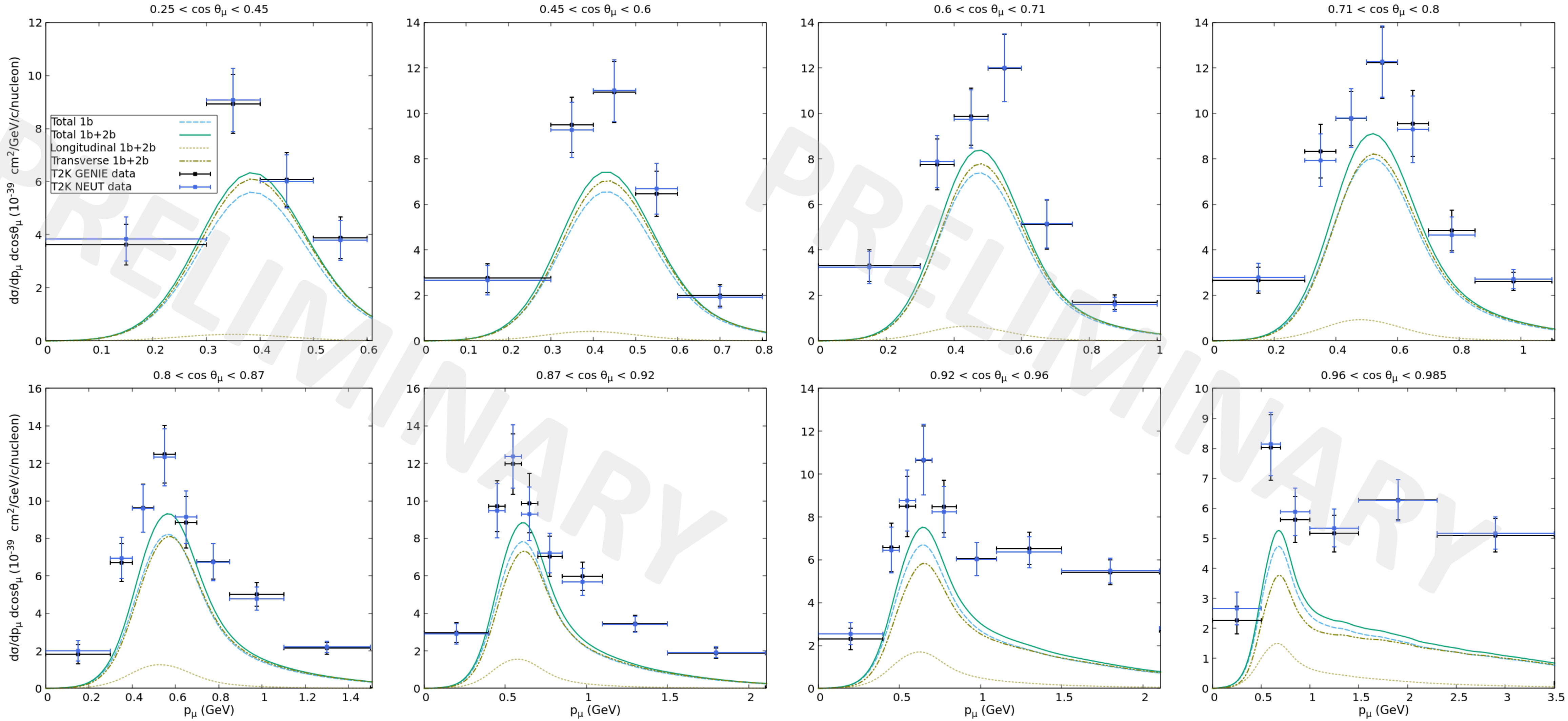
- Neutrino-nucleus scattering
  - **^{12}C inclusive cross section**

^{12}C-ν_μ CC inclusive cross section



T2K ^{12}C-ν_μ CC inclusive cross section



K. Abe et al. (T2K Collaboration), Phys. Rev. D 98, 012004 (2018)

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Conclusions and future prospects

- We have developed **a relativistic mean-field based model**, with **one- and two-body current** contributions to the **1p-1h** excitation.

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  - The use of a **realistic treatment of the nuclear structure** is fundamental to describe the experimental data.
  - **Two-body meson exchange** currents are only **significant** and produce an **increase** in the **transverse channel**.

Conclusions and future prospects

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- **Electron**-nucleus results:

Conclusions and future prospects

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- Next steps: **^{40}Ar** and continuing with **neutrino-nucleus** scattering.

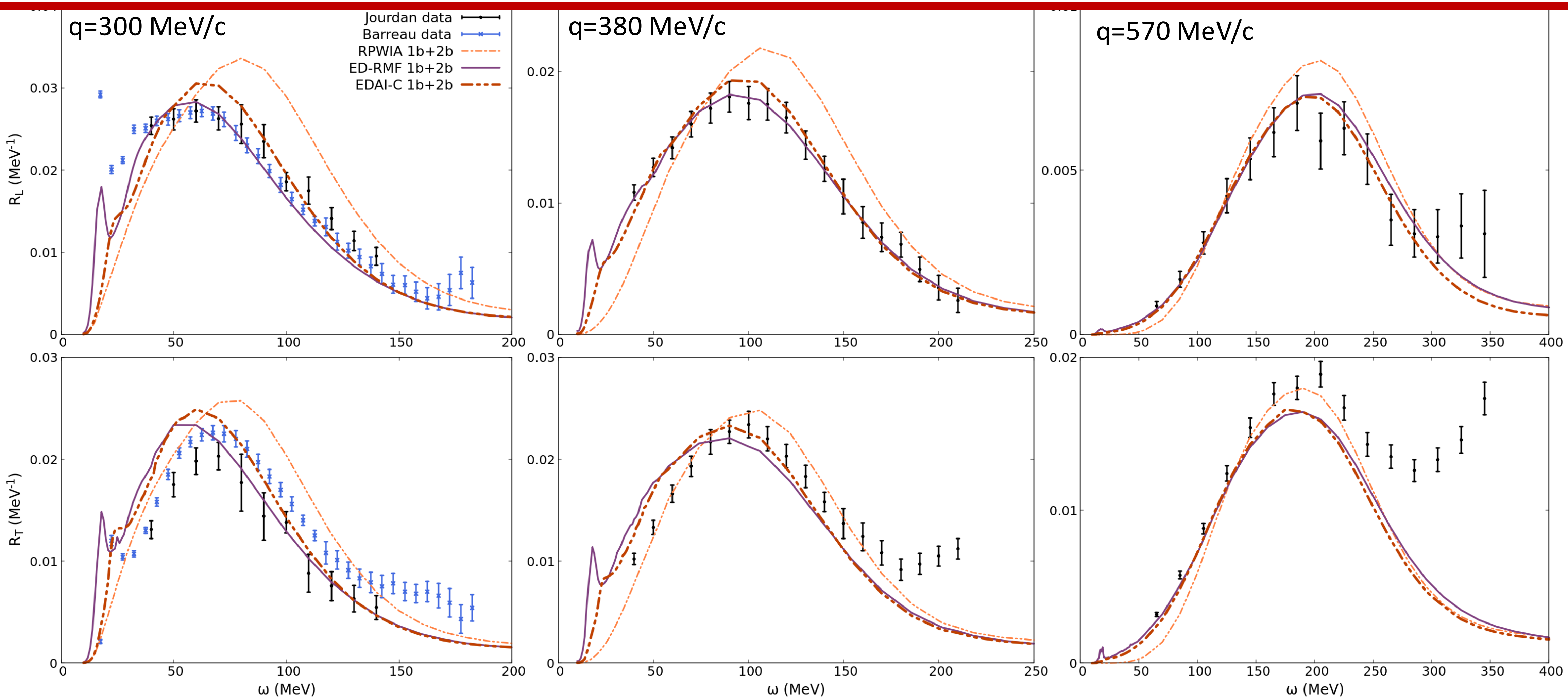
Thanks for your attention !

Backup

^{12}C results

Quantum mechanics in the final nucleon

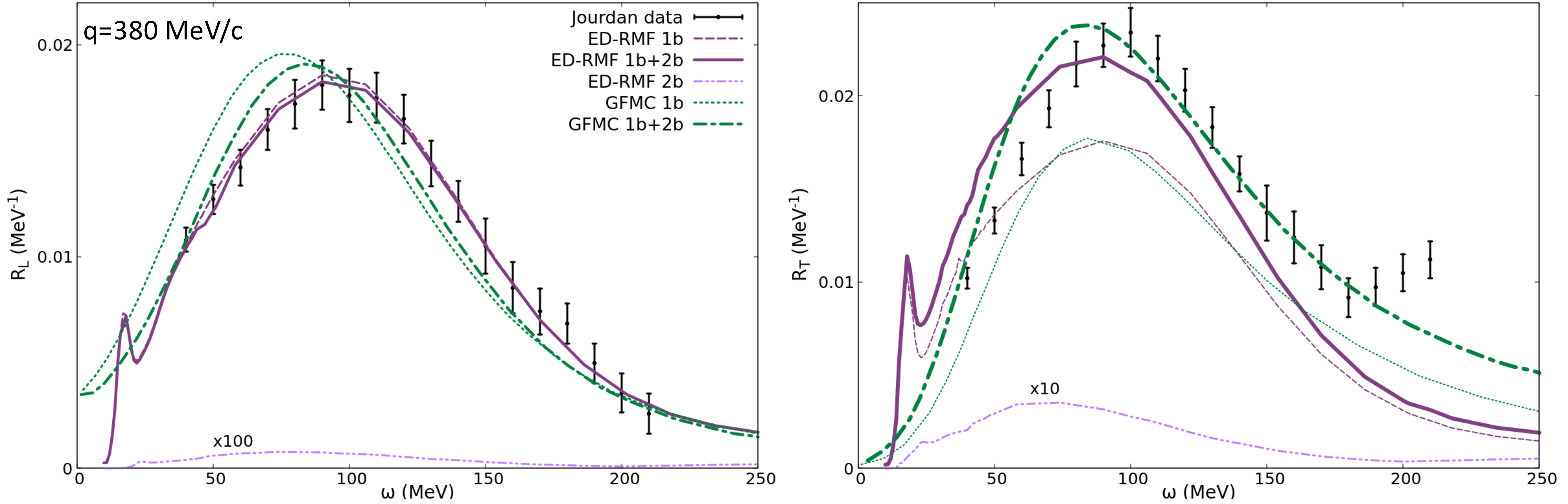
Spurious contributions appear from **non-orthogonality** between initial and final states



EDAI-C: E. D. Cooper, S. Hama, B. C. Clark, and R. L. Mercer, Phys. Rev. C 47, 297 (1993).

Comparison to previous computations

- Two completely different theoretical approaches
  - **Ab initio non-relativistic Green's function Monte Carlo** (GFMC).
  - **ED-RMF**: fully **relativistic model** and coherent **quantum mechanical** description of the nucleonic states, incorporating **realistic dynamics and final state interactions**



- Remarkable good agreement between both ED-RMF and GFMC calculations

GFMC: A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, and R. Schiavilla, Phys. Rev. Lett. 117, 082501 (2016).

^{12}C electromagnetic cross section

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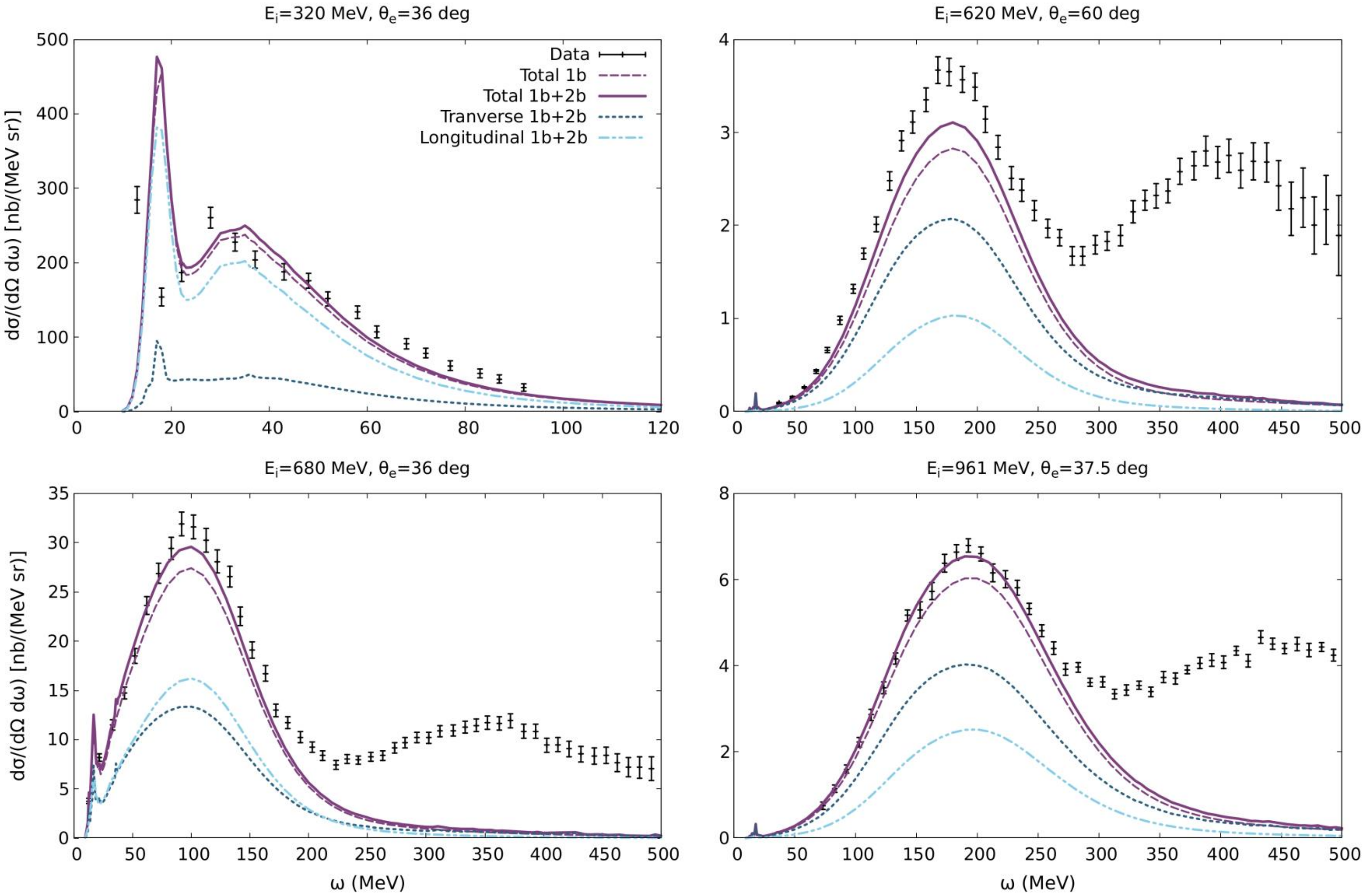

Data: P. Barreau et al., Nuclear Physics A 402 (3) (1983)
R. M. Sealock et al., Phys. Rev. Lett. 62 (1989)

^{40}Ca results

^{40}Ca electromagnetic inclusive responses

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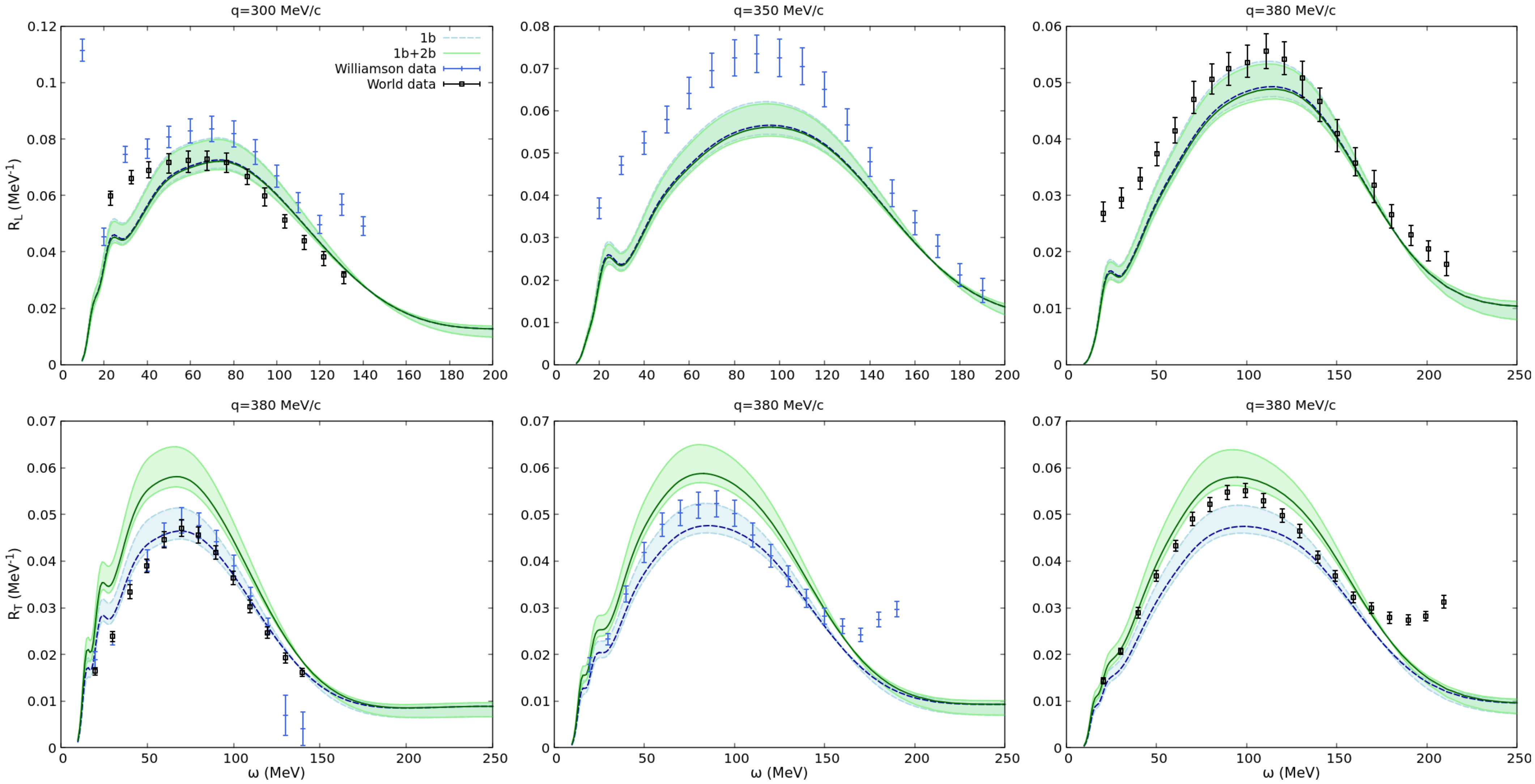
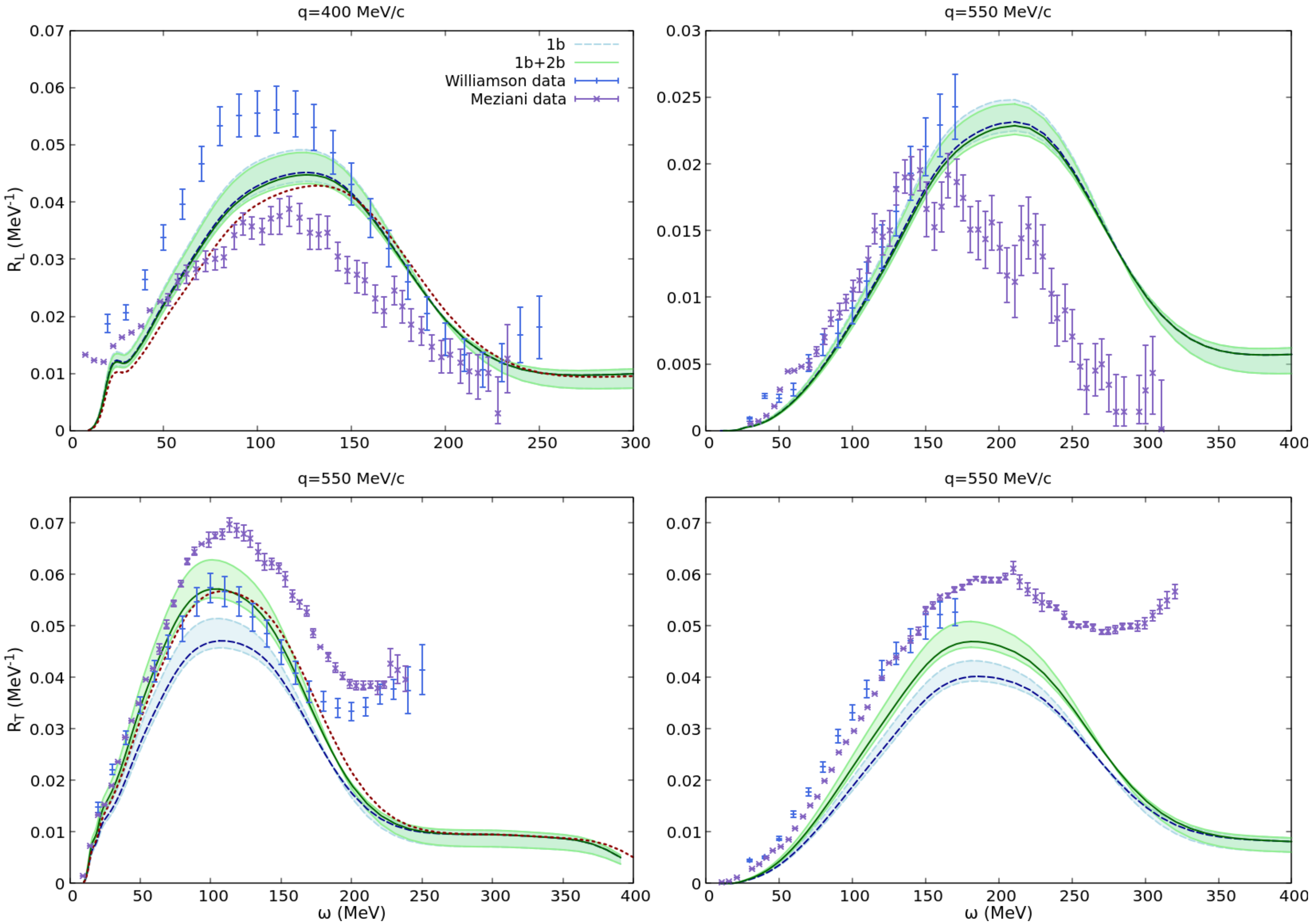


J. Jourdan, Nucl. Phys. A 603, 117 (1996)
C. F. Williamson et al., Phys. Rev. C 56, 3152 (1997)

^{40}Ca electromagnetic inclusive responses



C. F. Williamson et al., Phys. Rev. C 56, 3152 (1997)
Z. E. Meziani et al., Phys. Rev. Lett. 52, 2130 (1984)
Z. E. Meziani et al., Phys. Rev. Lett. 54, 1233 (1985)