Meson exchange currents within a relativistic mean-field model in the quasielastic regime

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

MITP Topical Workshop: Neutrino Scattering at Low and Intermediate Energies

Reference paper

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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]

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Departamento de Estructura de la Materia,
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[2] *Department of Physics and Astronomy,*
Ghent University, B-9000 Gent, Belgium

(Dated: June 21, 2023)

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 (RMF) 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.

arXiv.2306.10823

Reference paper

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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]

[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*

(Dated: June 28, 2023)

Longitudinal and transverse responses from inclusive electron scattering are computed within an independent-particle relativistic mean-field model to describe the initial and final states, and one- and two-body current operators leading to the one-particle one-hole response. We find that the two-body contributions have no effect on the longitudinal response but they increase the transverse response by up to 30%, depending on the energy and momentum transfer, improving very significantly the agreement with experimental data. Our calculation is fully relativistic and considers within the full quantum mechanical description both the initial and final nucleon states involved in the process, incorporating realistic dynamics. We also show that it is essential to go beyond the plane-wave approach, as incorporating the distortion of the nucleons while making the initial and final states orthogonal, allows to reproduce both the shape and magnitude of the responses. The good agreement with the electron scattering experimental data supports the use of this approach to describe neutrino-induced scattering reaction.

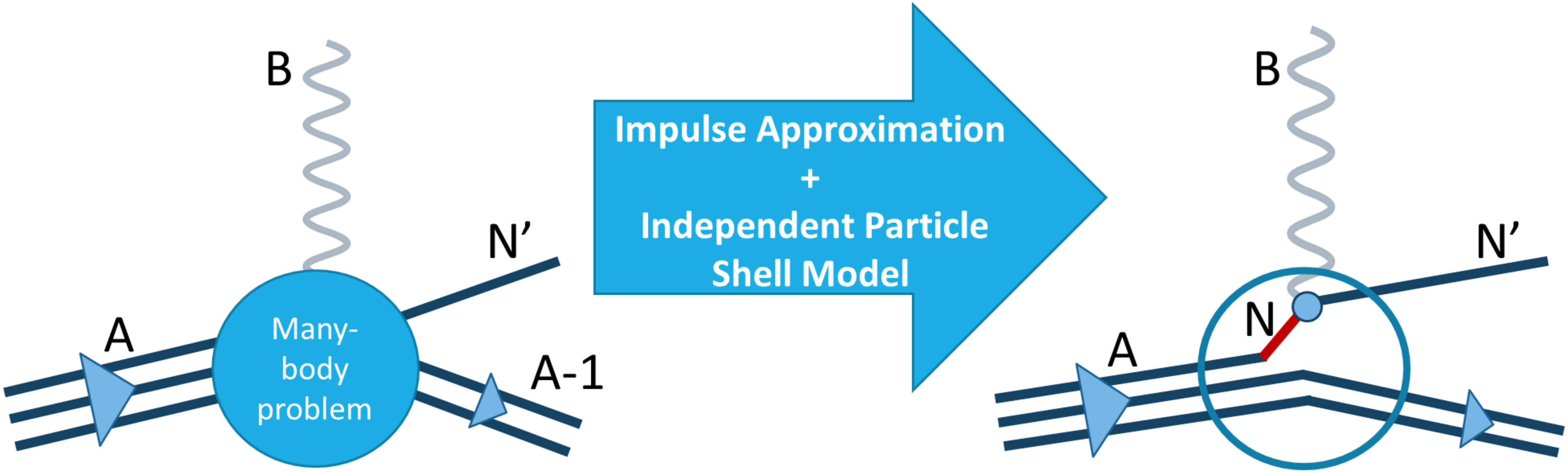
arXiv.2203.09996

Outline

- **Theoretical framework** (nuclear model): relativistic mean-field model.
- Two-body **meson-exchange currents** in particle-hole excitations.
- **^{12}C electromagnetic inclusive responses**:
  - Different approaches for the two-body current operator.
  - Relevance of quantum mechanics in the final nucleon.
- **^{40}Ca electromagnetic inclusive cross section**.
- Conclusions and future prospects.

Nuclear model

- We **focus on quasielastic** scattering.



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

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

Nuclear model

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

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

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

Nuclear model

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

- **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.

ED-RMF: R.González-Jiménez et al. Phys. Rev. C 100, 045501 (2019).

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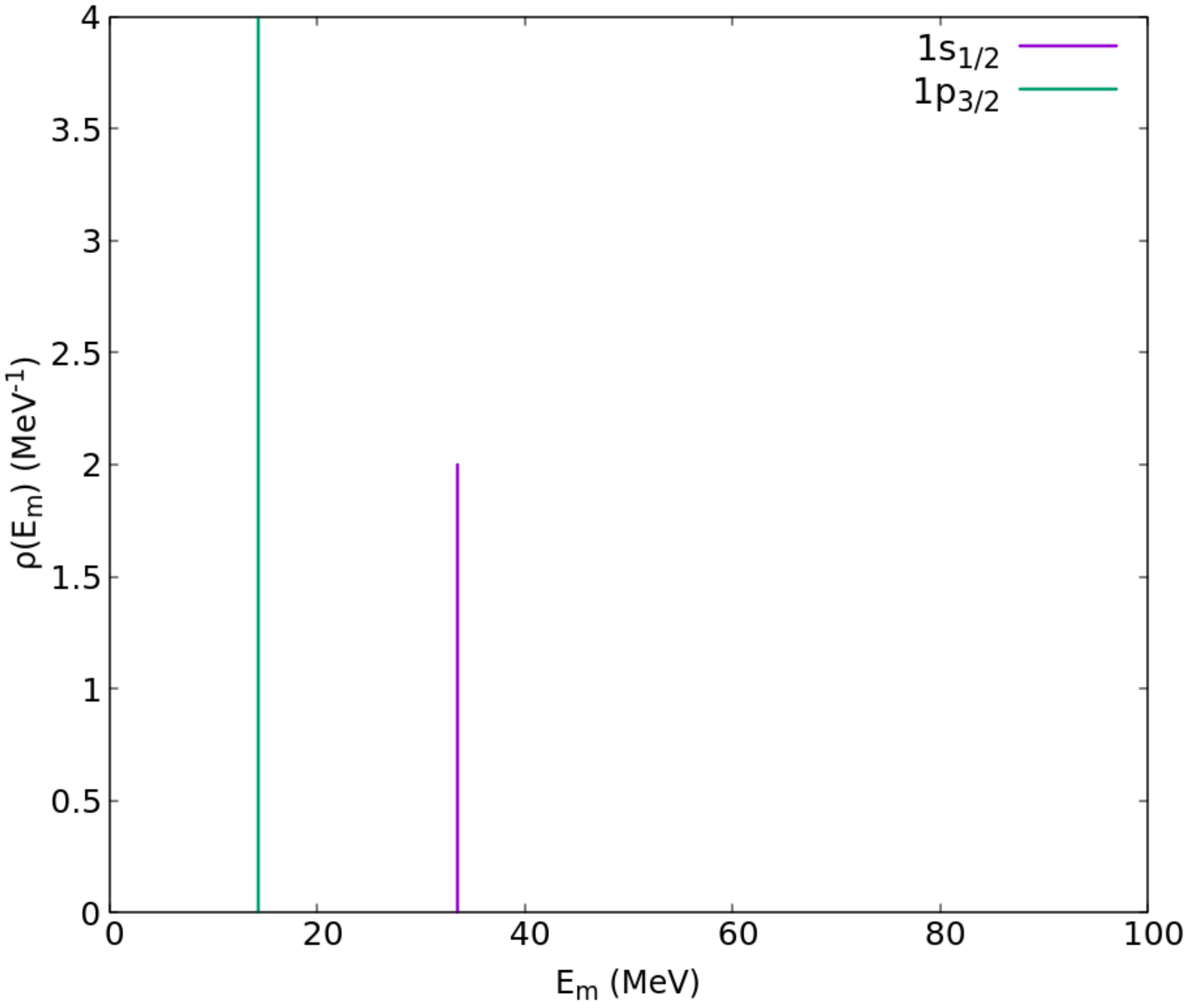
$$J^{\mu}_{had} \sim \overline{\Psi}^{s}(\boldsymbol{p}'_N, \boldsymbol{p}_N)\, \Gamma^{\mu}\, \Psi^{\kappa}_{m_j}(\boldsymbol{p})$$

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

Nuclear structure

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

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



Nuclear structure

- Nuclear structure in a pure shell mod

  - Oc

  - Mi

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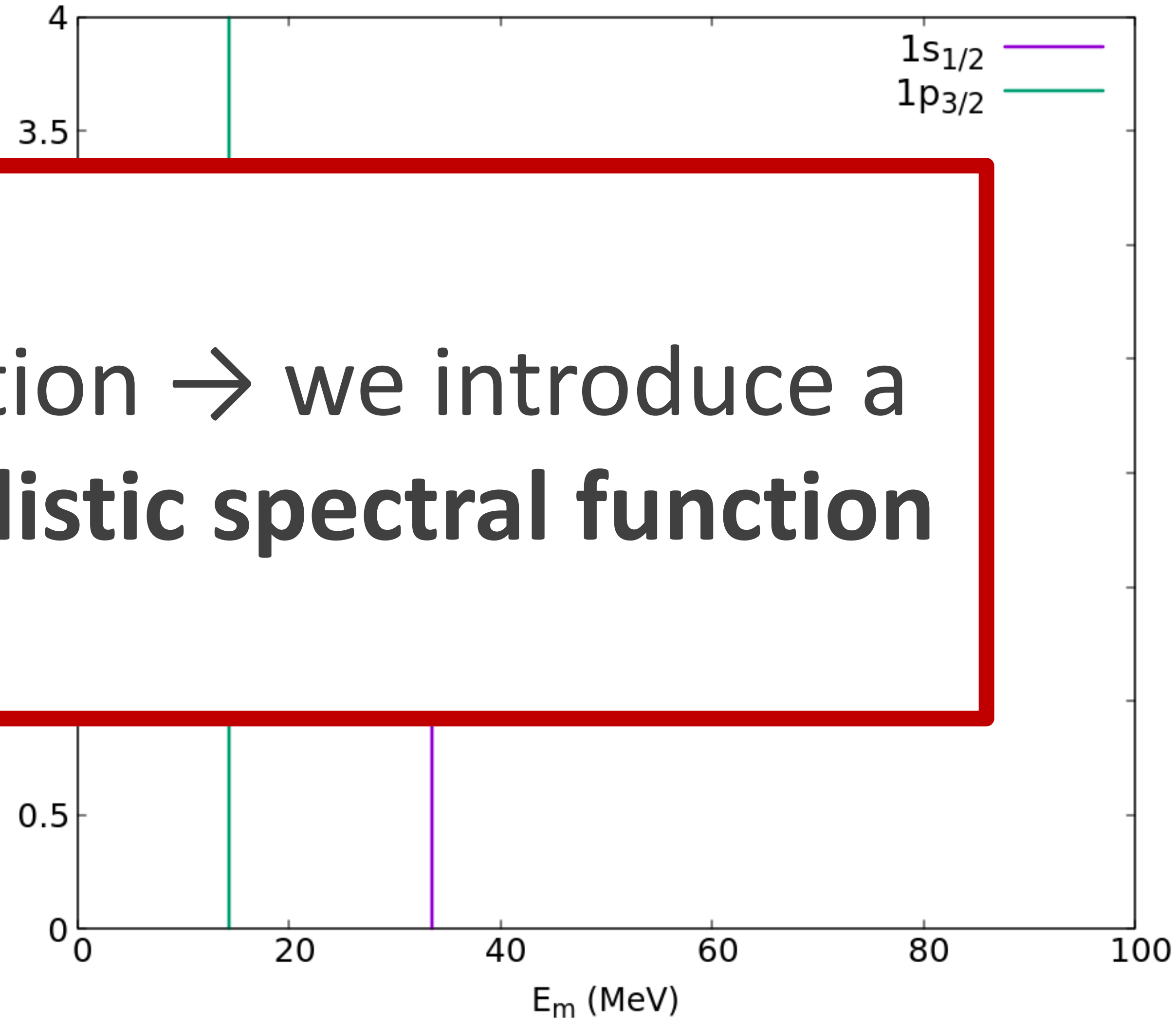
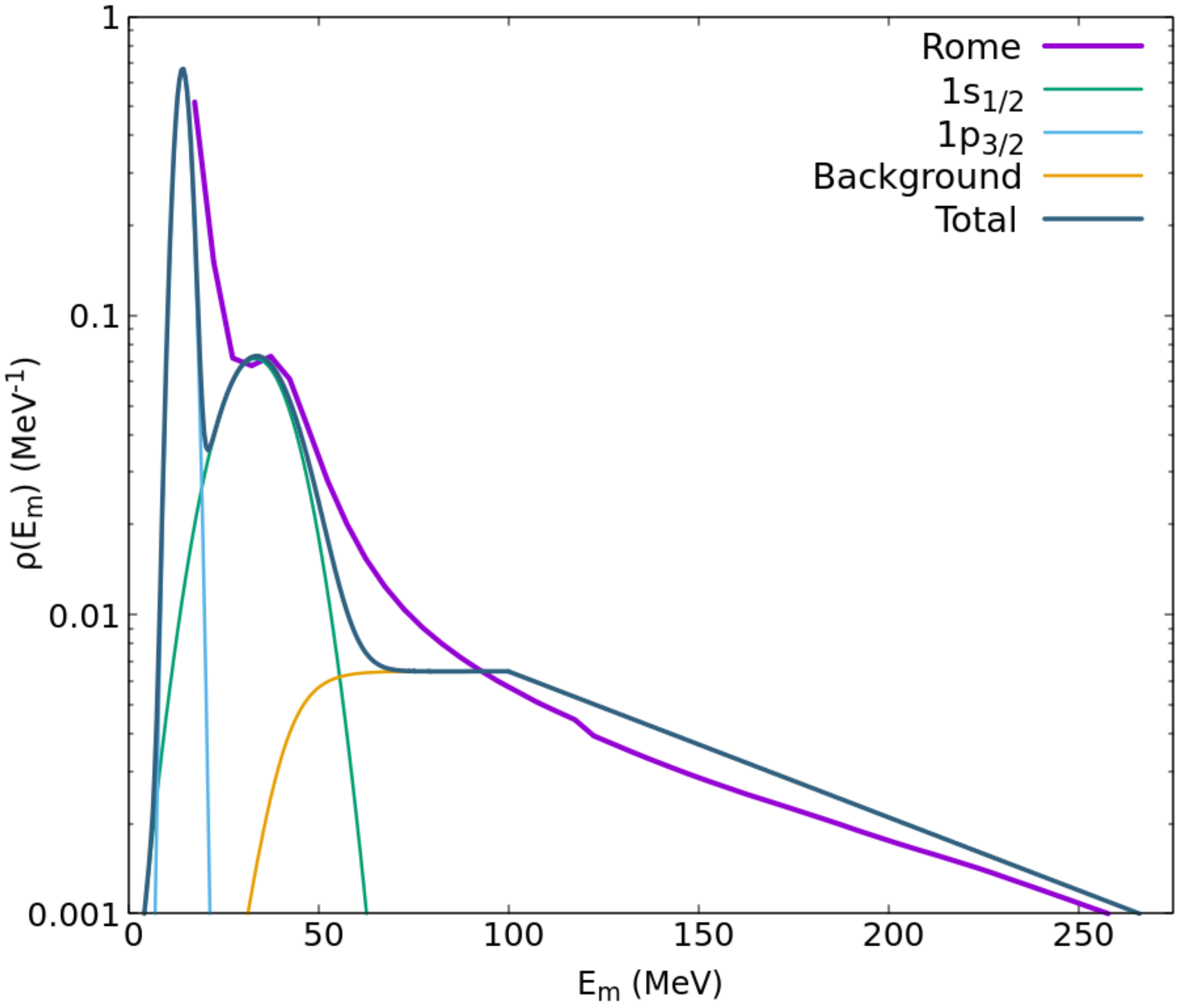


Simplistic approximation → we introduce a model based on a **realistic spectral function**

Nuclear structure

- 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).

Nuclear structure

- Nuclear structure based on a realistic spectral function:
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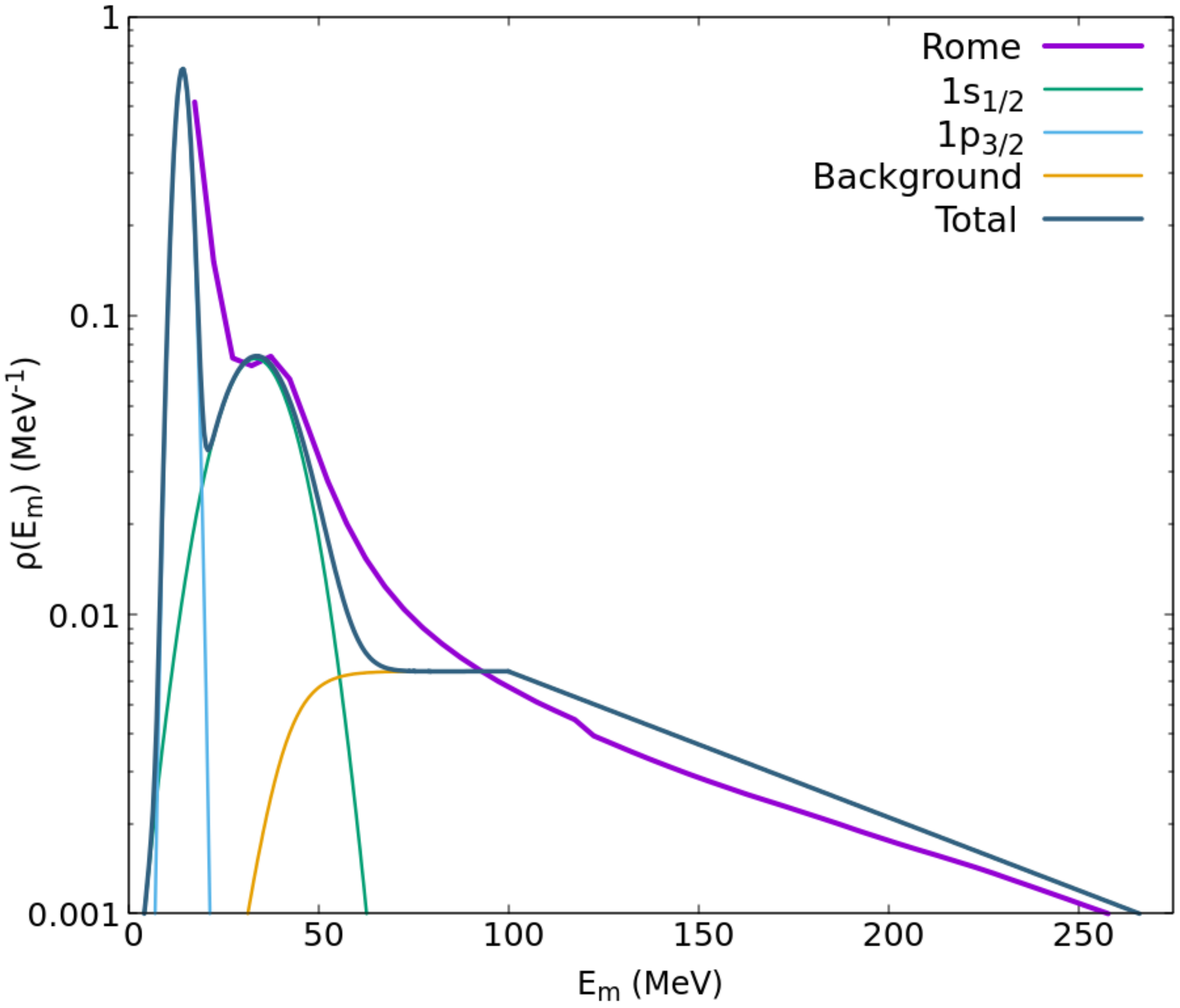
  - **Continuous missing energy profile**



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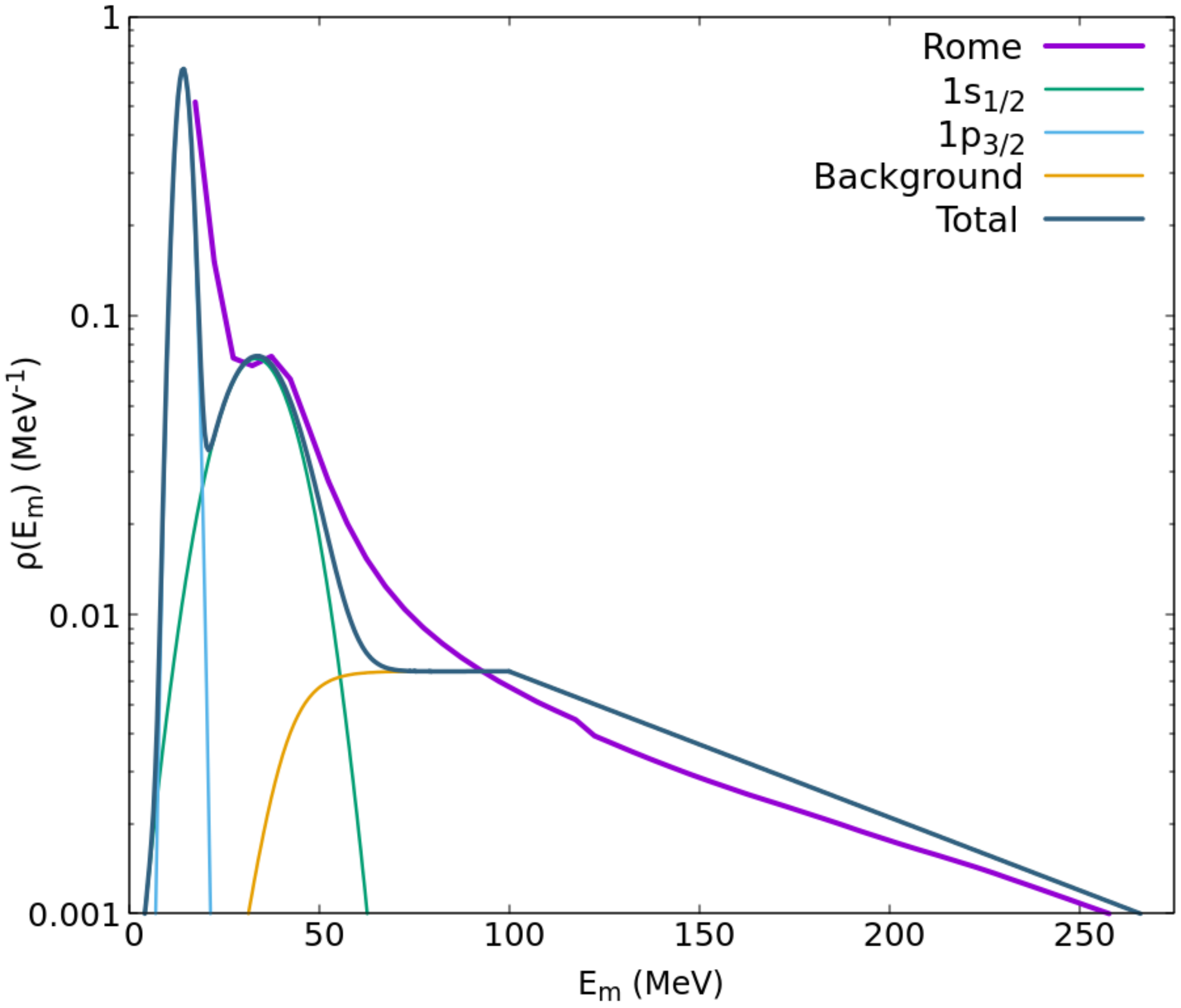
  - **Background due to short range correlations**
    - 0.9 nucleons



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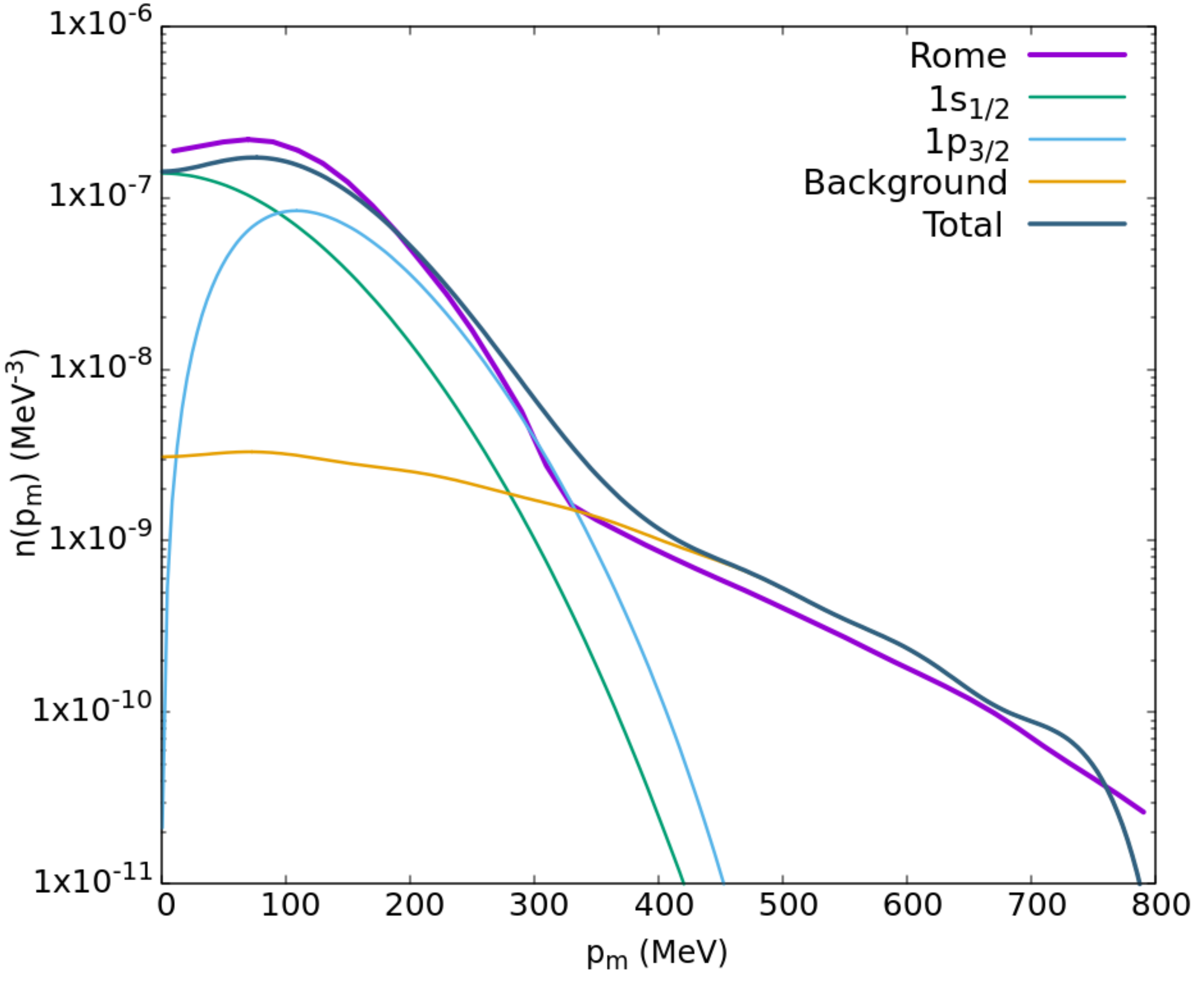

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Meson exchange currents

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

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

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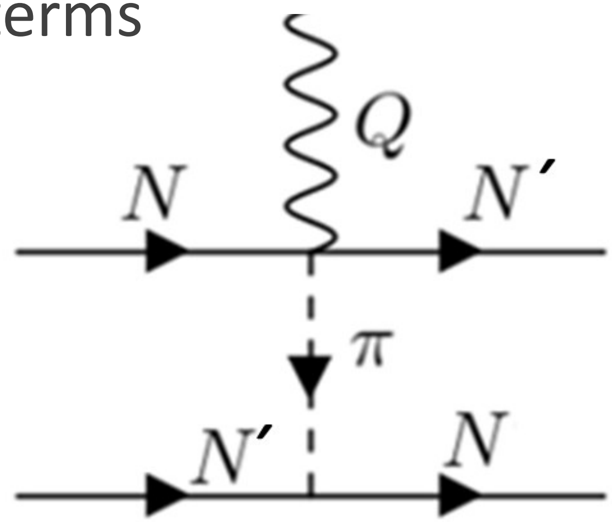

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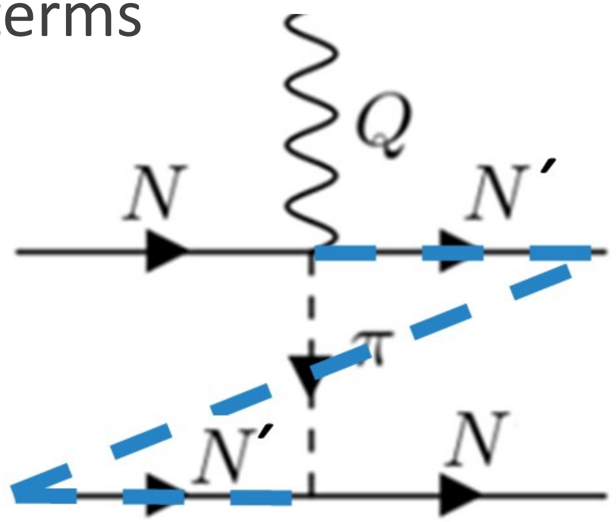

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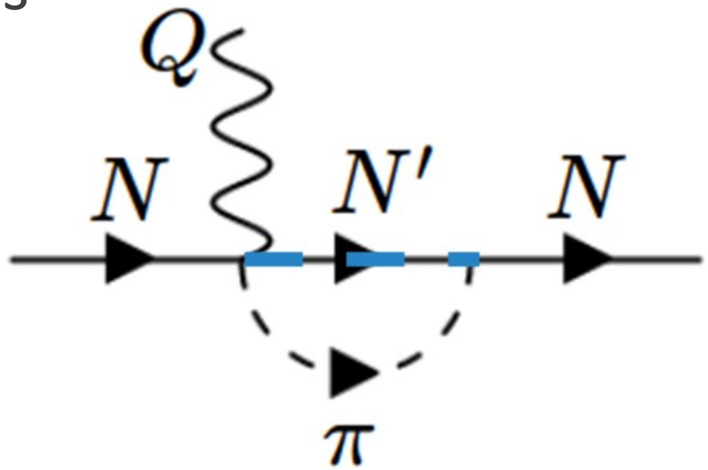

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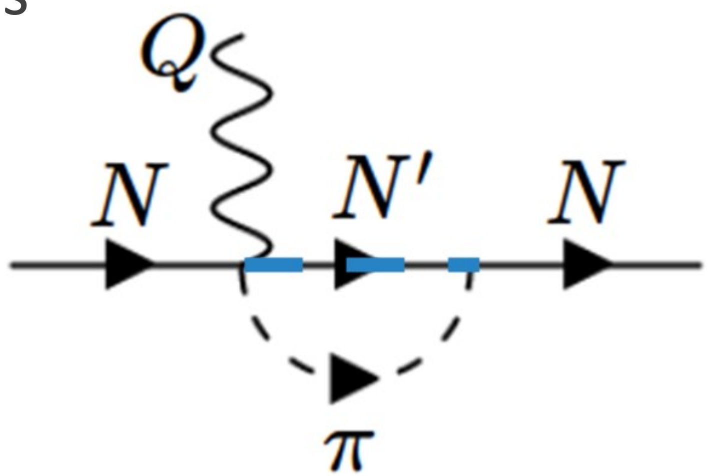
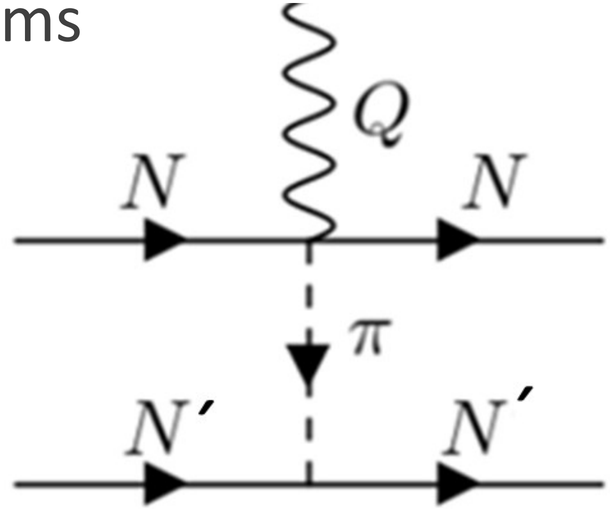


- Direct terms



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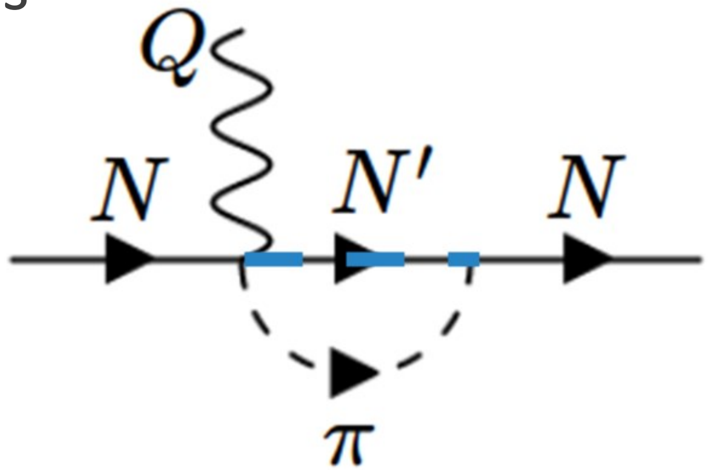

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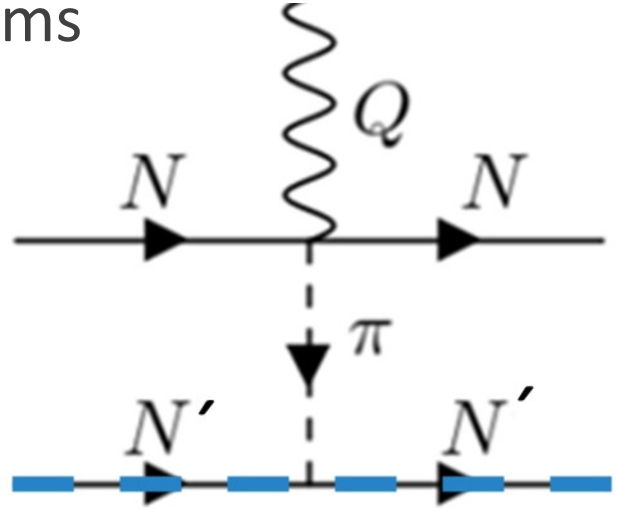

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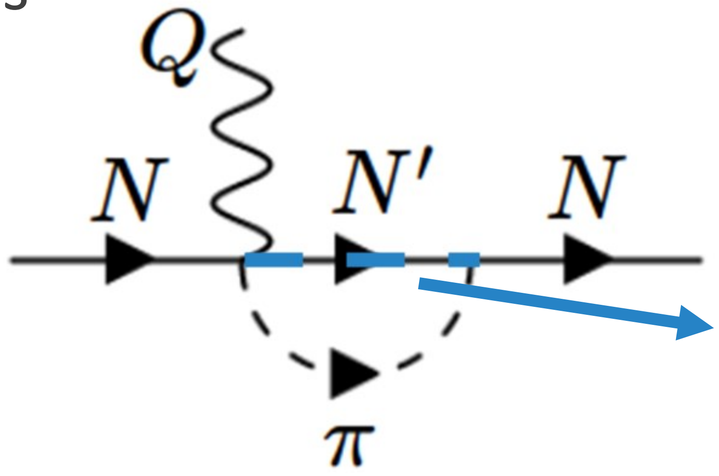
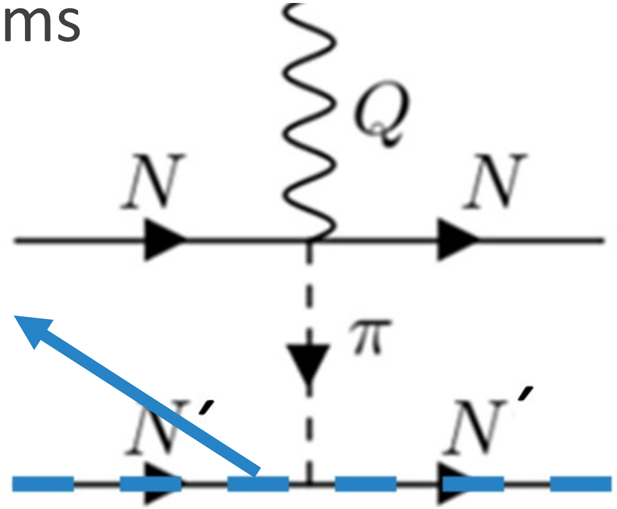


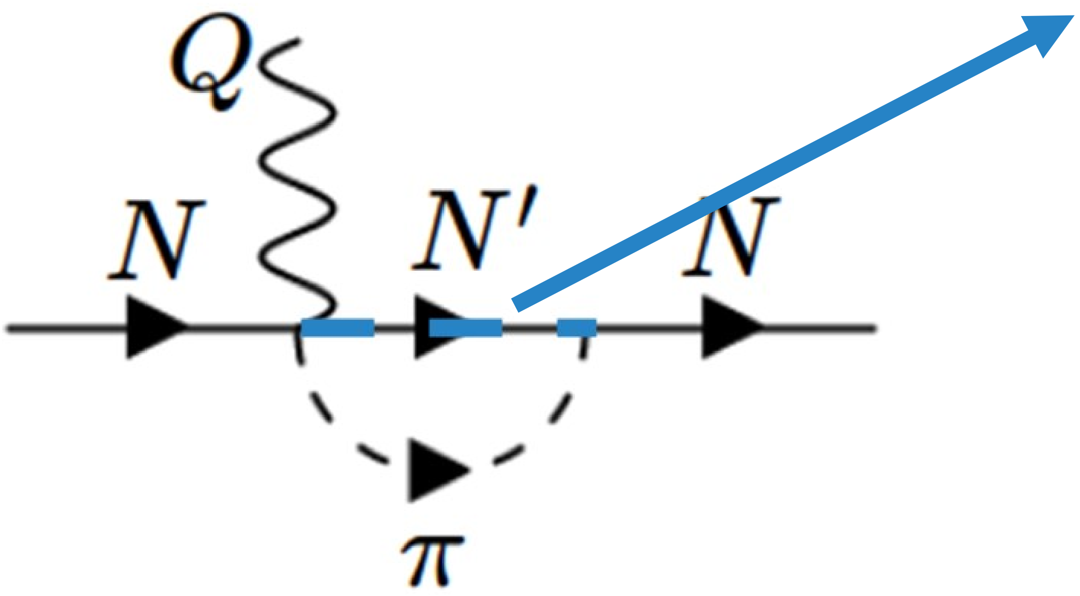
Intermediate bound-nucleon state

- Direct terms



Intermediate bound-nucleon state

- Different **approaches** for the treatment of the **intermediate bound-nucleon state.**



More realistic case:
Intermediate RMF-nucleon approach

Simplified case:
Intermediate RFG-nucleon approximation

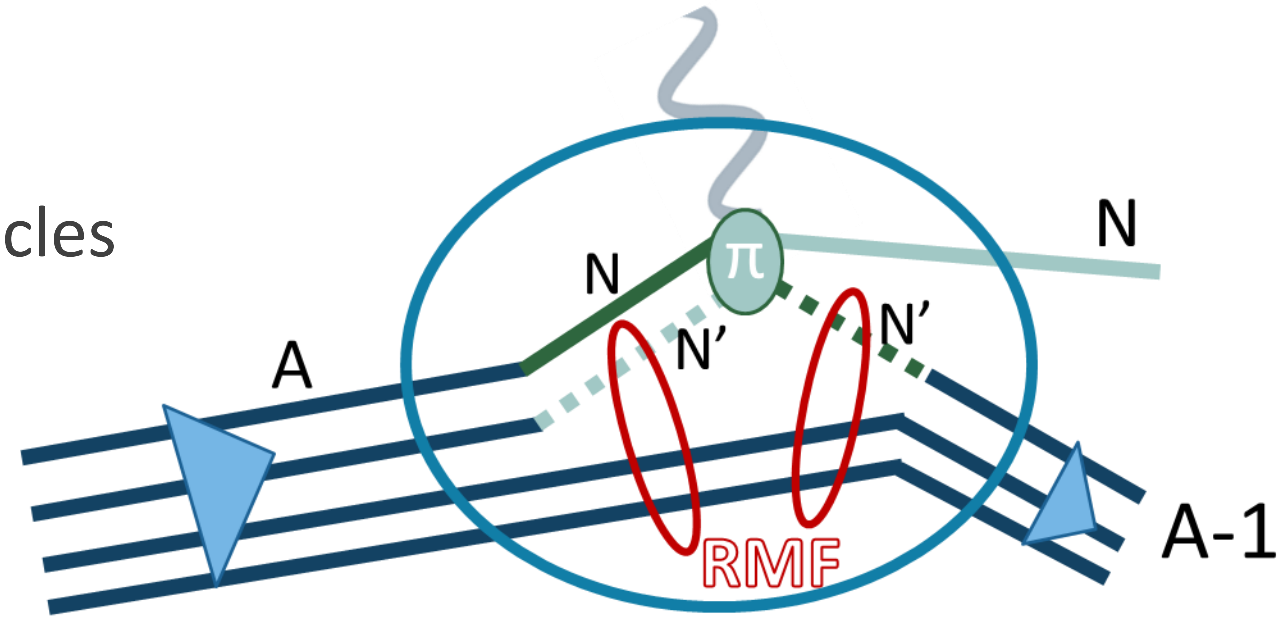
Approximated nuclear effects case:
Intermediate RFG*-nucleon approximation

Intermediate bound-nucleon state

More realisitic case:

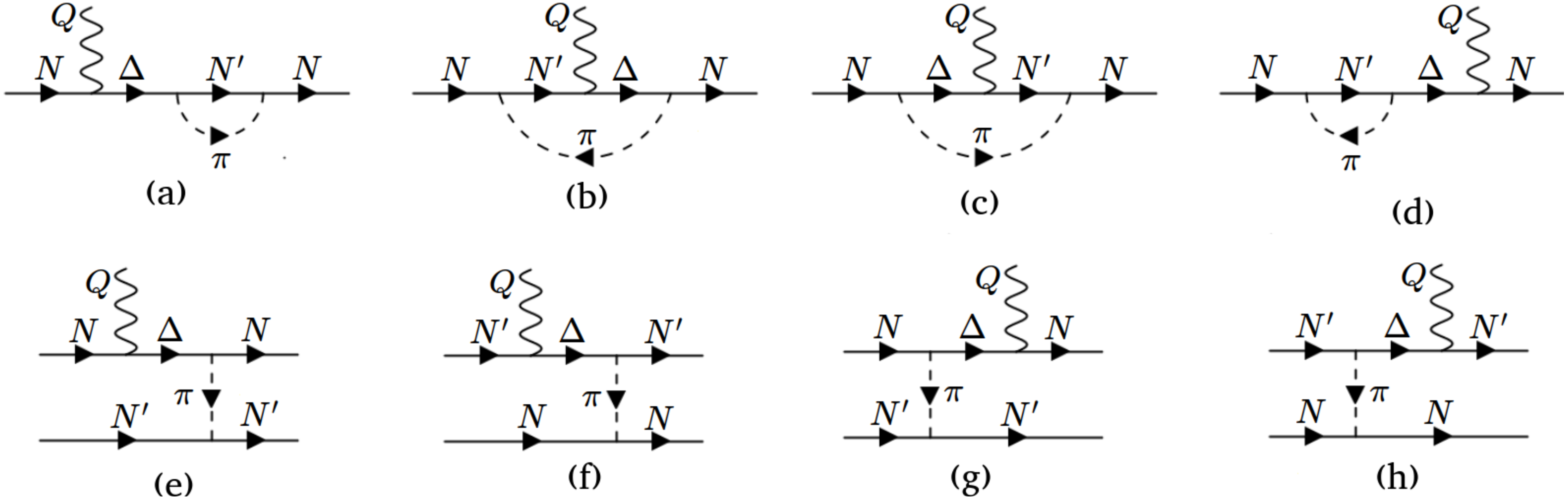
Intermediate RMF-nucleon approach

- The **intermediate bound** particles are described by **RMF spinors**.

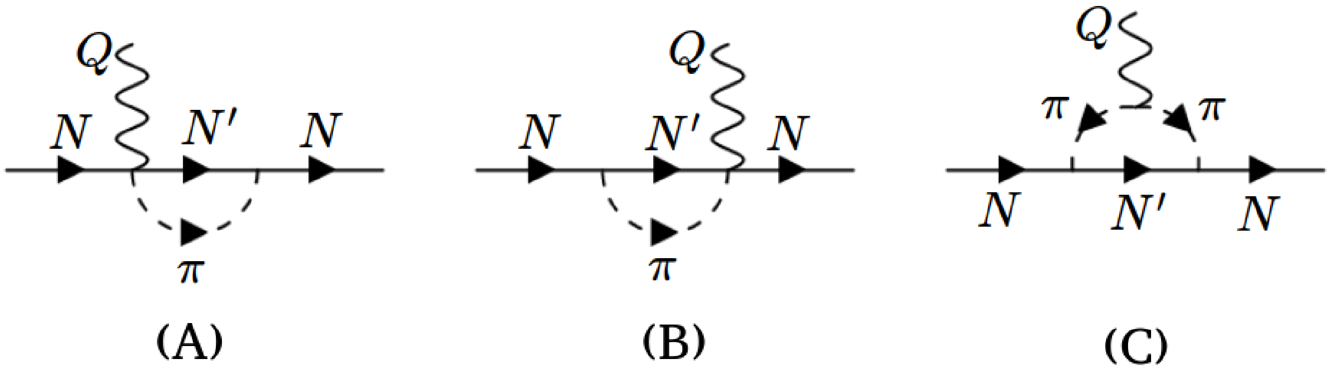


Intermediate RMF-nucleon approach

- **MEC contributions**
  - Delta resonance mechanism



  - ChPT background



Intermediate RMF-nucleon approach

- Two-body current

$$J_{2b}^{\mu} = \int d\boldsymbol{p} \int \frac{d\boldsymbol{p_p}}{(2\pi)^{3/2}} \int \frac{d\boldsymbol{p_h}}{(2\pi)^{3/2}} \bar{\Psi}^{s}(\boldsymbol{p} + \boldsymbol{p_h} + \boldsymbol{q} - \boldsymbol{p_p}, \boldsymbol{p_N}) \Gamma_{2b}^{\mu} \, \Psi_{\kappa}^{m_j}(\boldsymbol{p})$$

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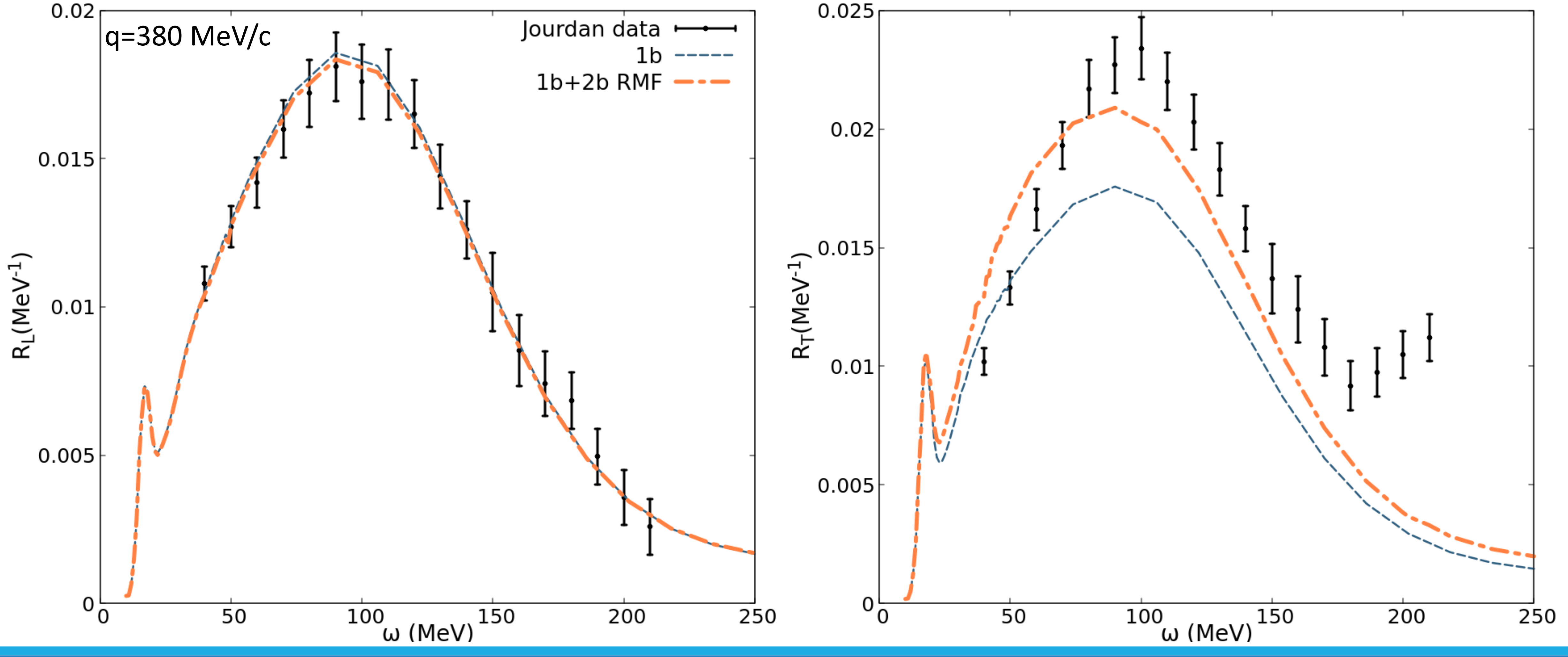
- **9-dimensional integral** → computational time and effort extremely high.

Intermediate RMF-nucleon approach

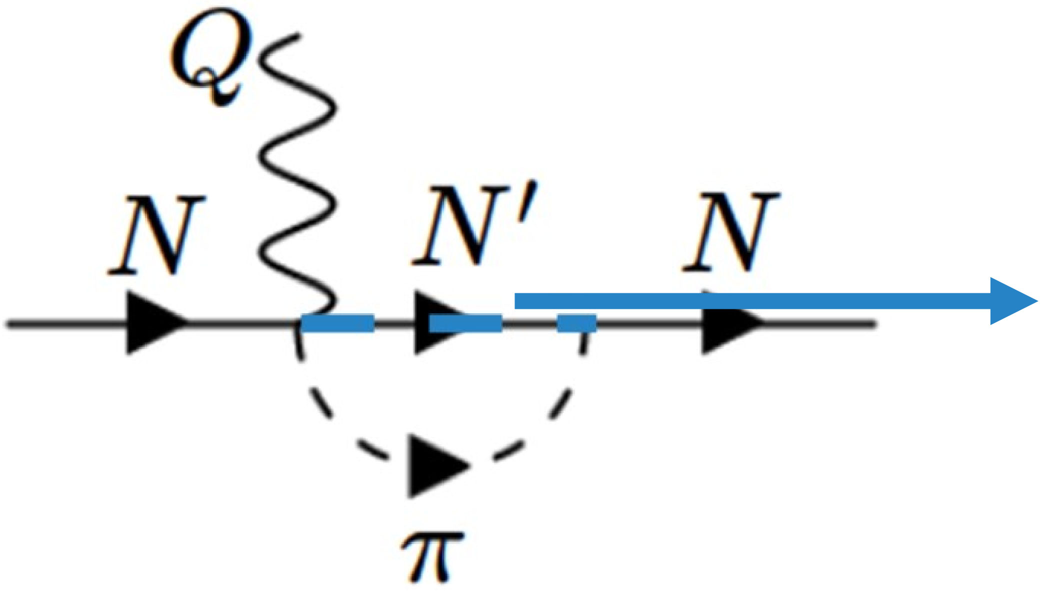
^{12}C electromagnetic inclusive responses



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

Intermediate bound-nucleon state

- Different **approaches** for the treatment of the **intermediate bound-nucleon state.**



More realistic case:
Intermediate RMF-nucleon approach

Simplified case:
Intermediate RFG-nucleon approximation

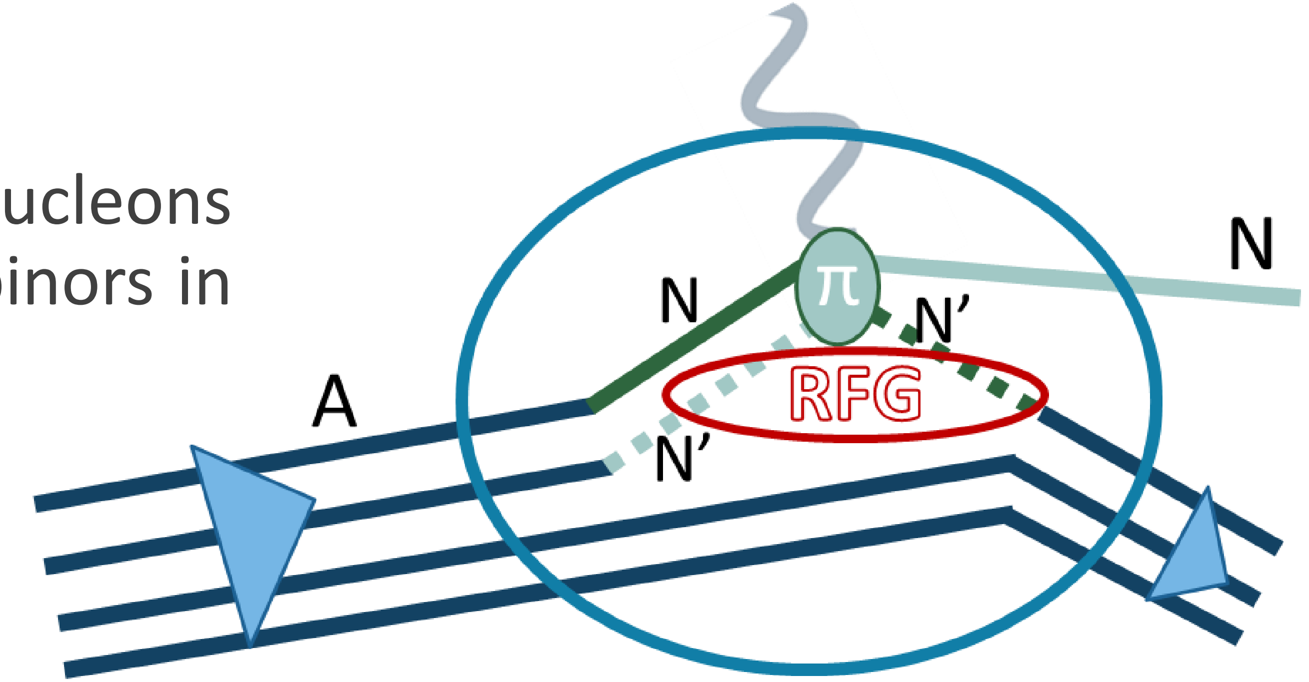
Approximated nuclear effects case:
Intermediate RFG*-nucleon approximation

Intermediate bound-nucleon state

Simplified case:

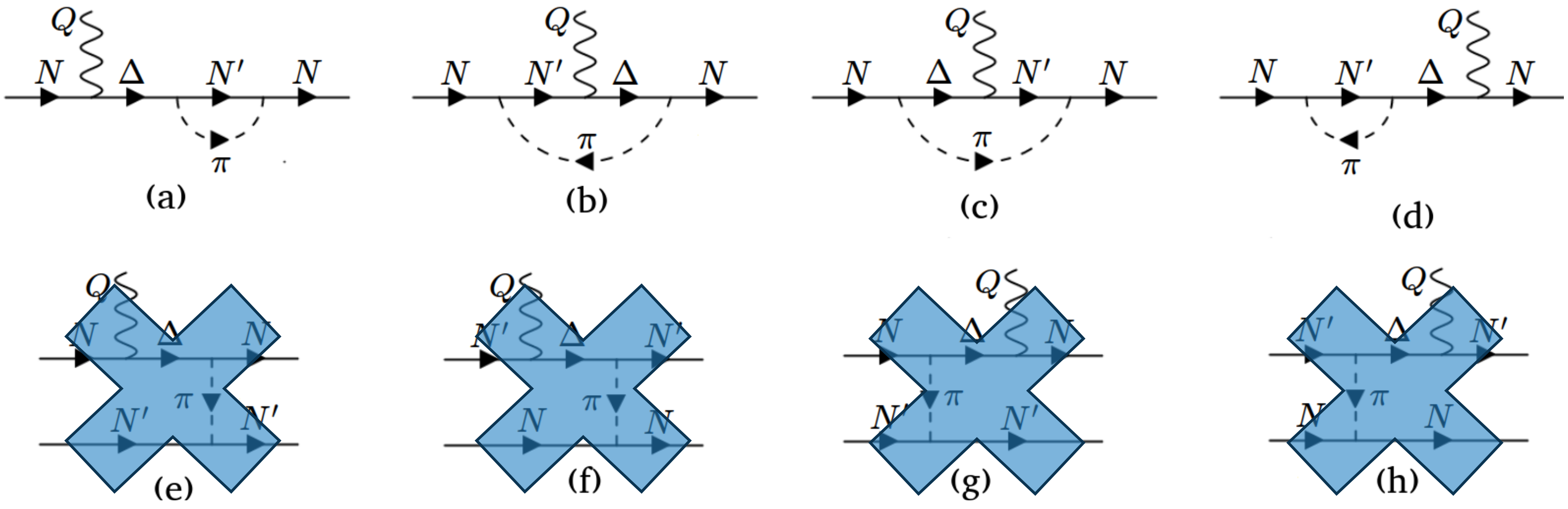
Intermediate RFG-nucleon approximation

- The **intermediate bound** nucleons are described as **free** Dirac spinors in a **relativistic Fermi gas (RFG)**.



Intermediate RFG-nucleon approximation

- **MEC contributions**
  - Delta resonance mechanism



  - ChPT background

Taking intermediate RFG nucleons the Delta-resonance direct terms vanish.

Intermediate RFG-nucleon approximation

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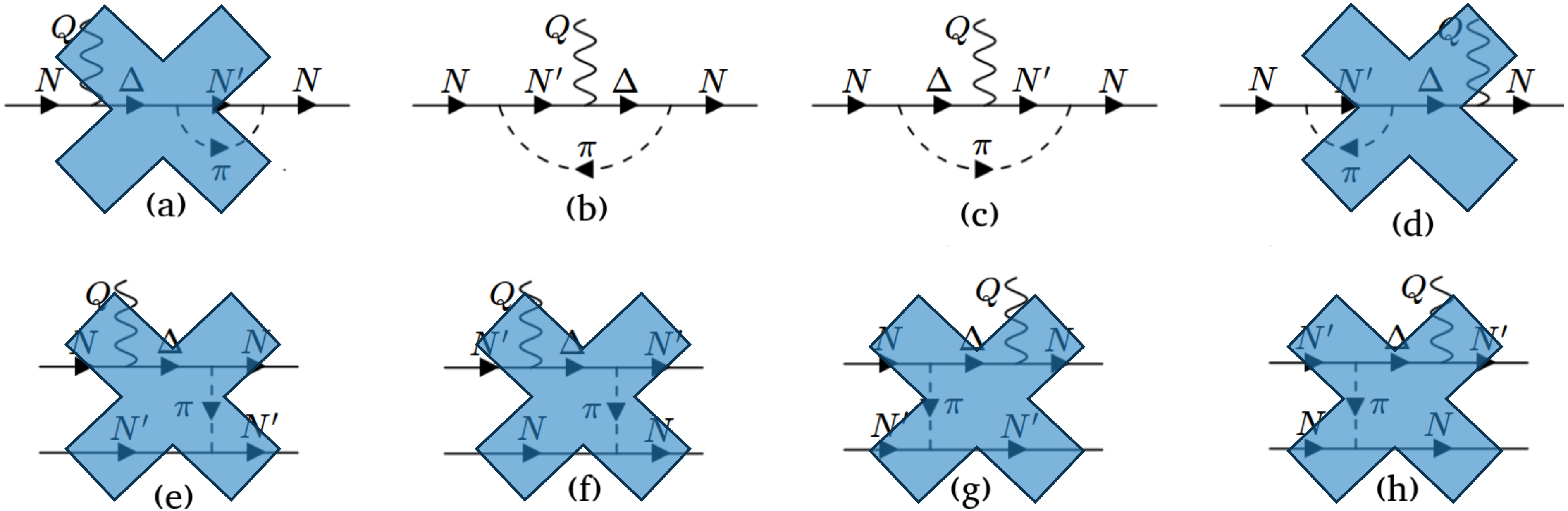
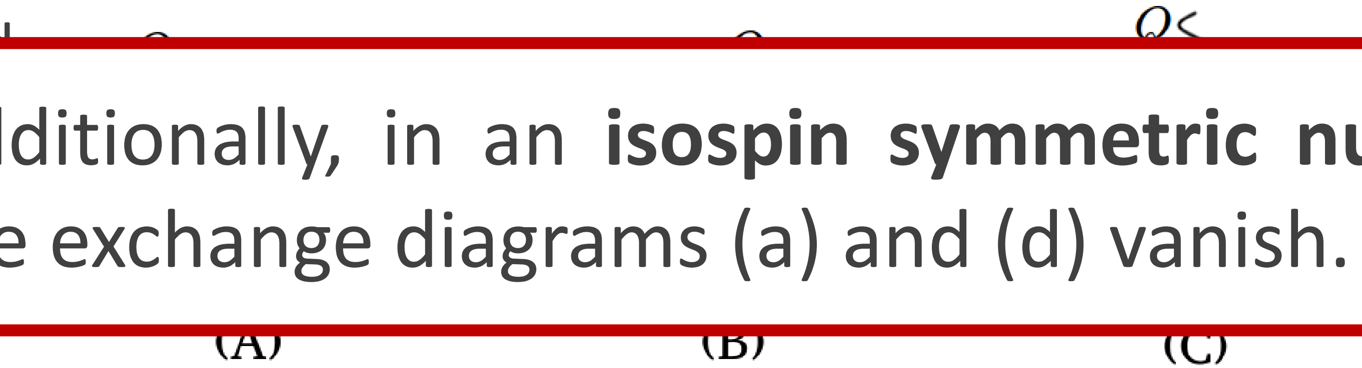


  - ChPT background



Additionally, in an **isospin symmetric nucleus,** the exchange diagrams (a) and (d) vanish.

Intermediate RFG-nucleon approximation

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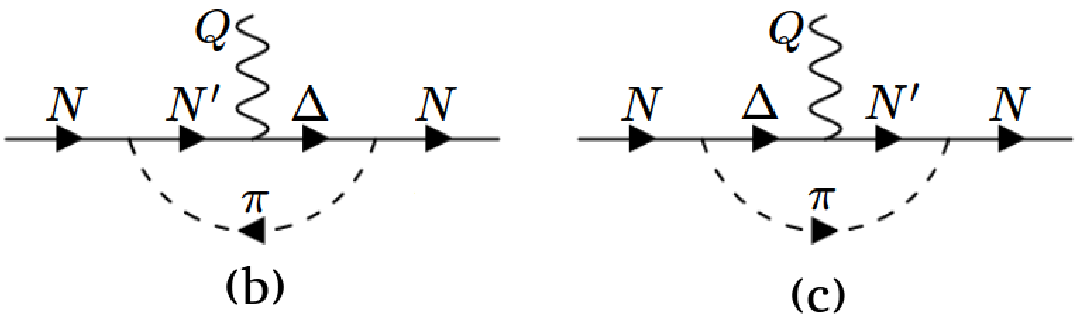
- **MEC contributions**
  - Delta resonance mechanism



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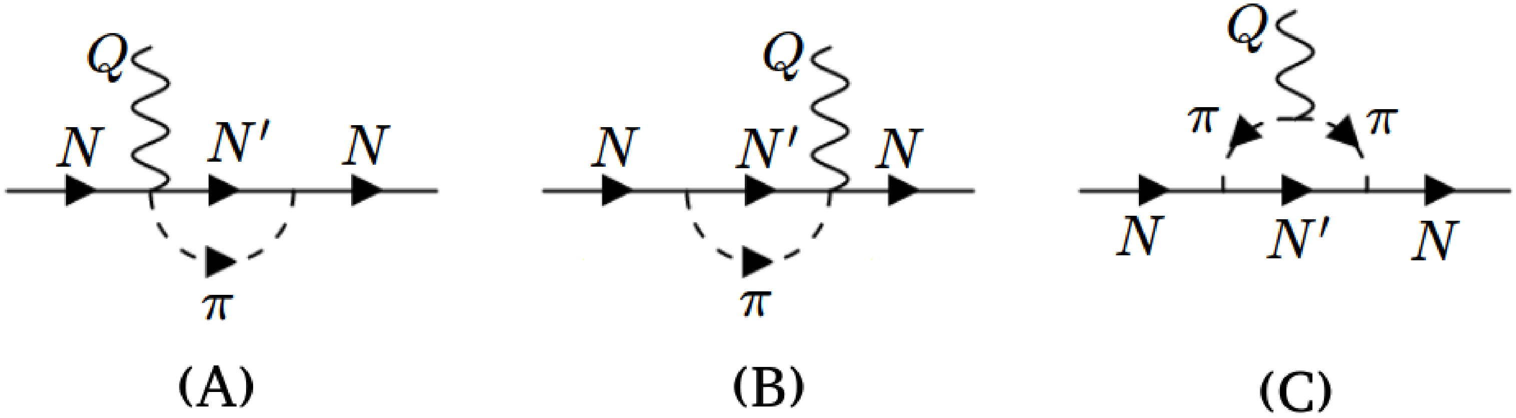

Intermediate RFG-nucleon approximation

- Two-body current

$$J^{\mu}_{2b,free} = \int d\boldsymbol{p} \int \frac{d\boldsymbol{p_{ph}}}{(2\pi)^3} \Theta(p_F - p_{ph})\, \bar{\Psi}^s(\boldsymbol{p}+\boldsymbol{q}, \boldsymbol{p_N}) \Gamma^{\mu}_{2b,free}\, \Psi^{m_j}_{\kappa}(\boldsymbol{p})$$

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- **6-dimensional integral** → computations can be done in a **more manageable** amount of time.

Intermediate RFG-nucleon approximation

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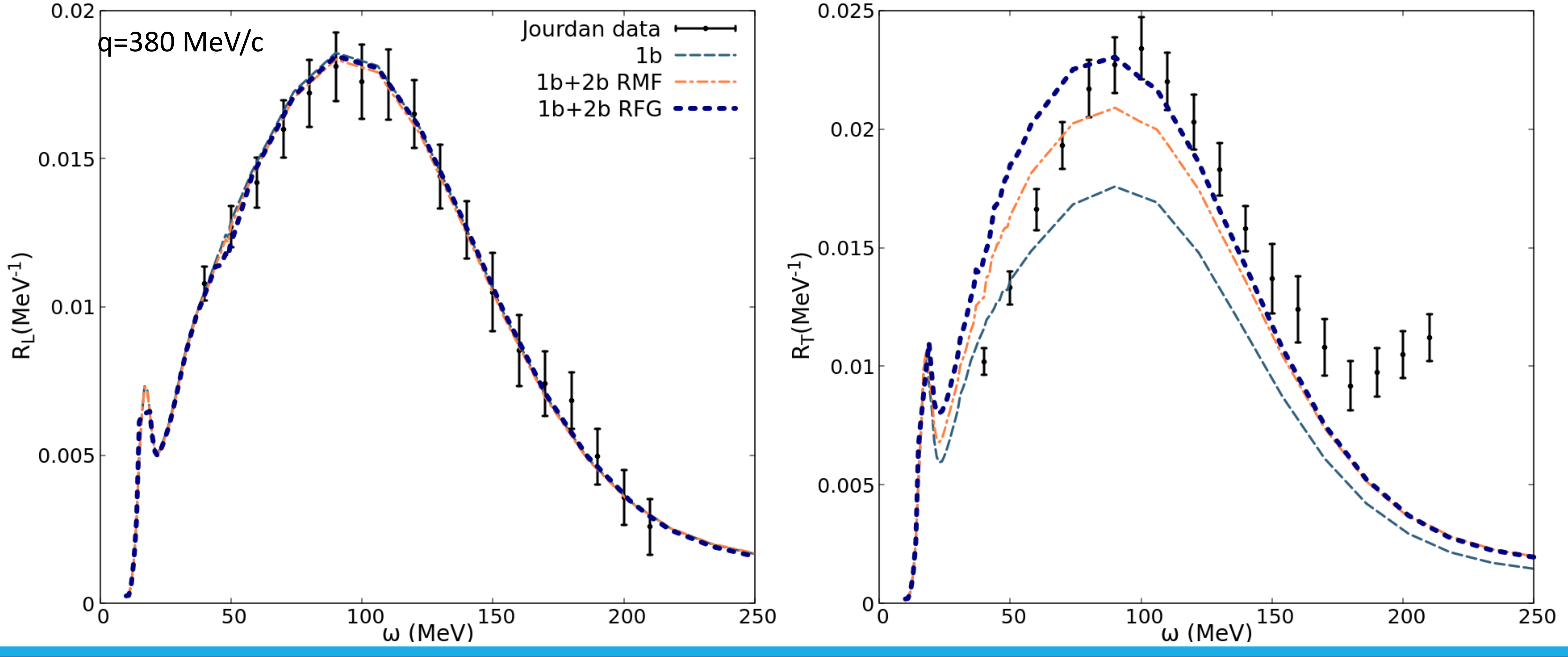
^{12}C electromagnetic inclusive responses



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Intermediate bound-nucleon state

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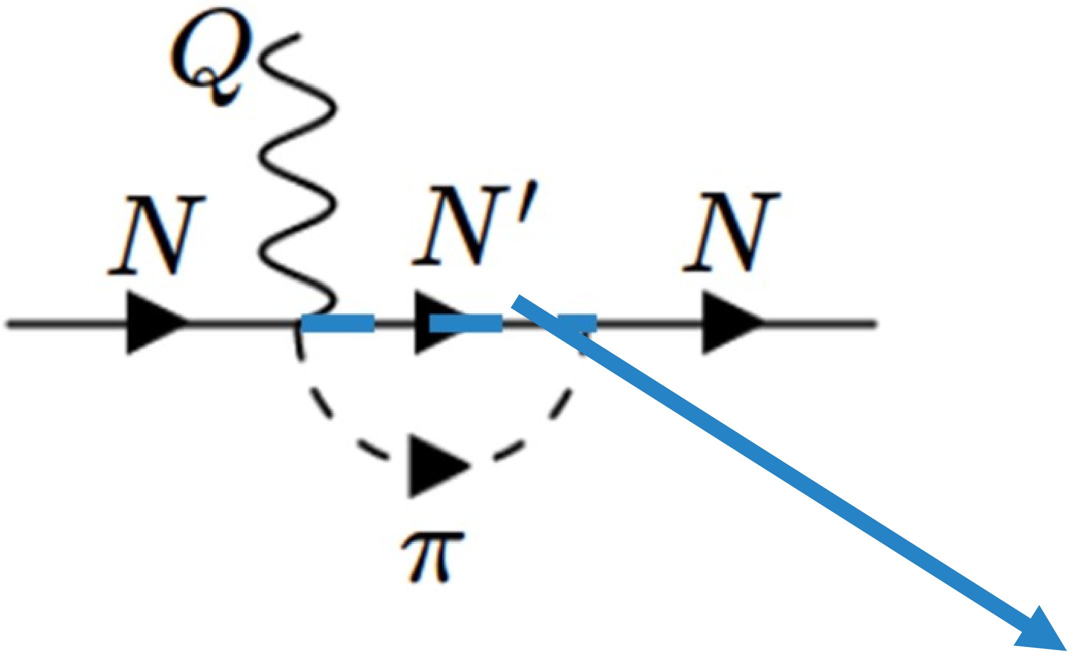


More realistic case:
Intermediate RMF-nucleon approach

Simplified case:
Intermediate RFG-nucleon approximation

Approximated nuclear effects case:
Intermediate RFG*-nucleon approximation

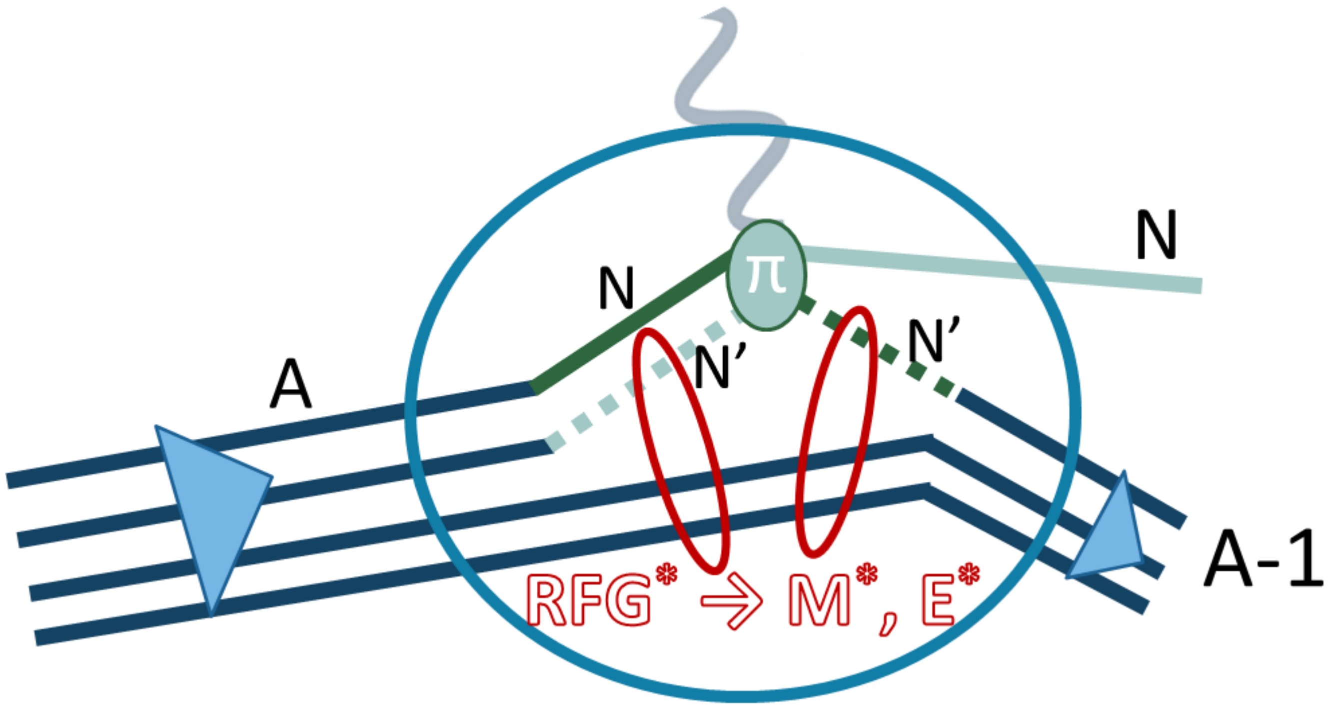
Intermediate bound-nucleon state

Approximated nuclear effects case:

Intermediate RFG*-nucleon approximation

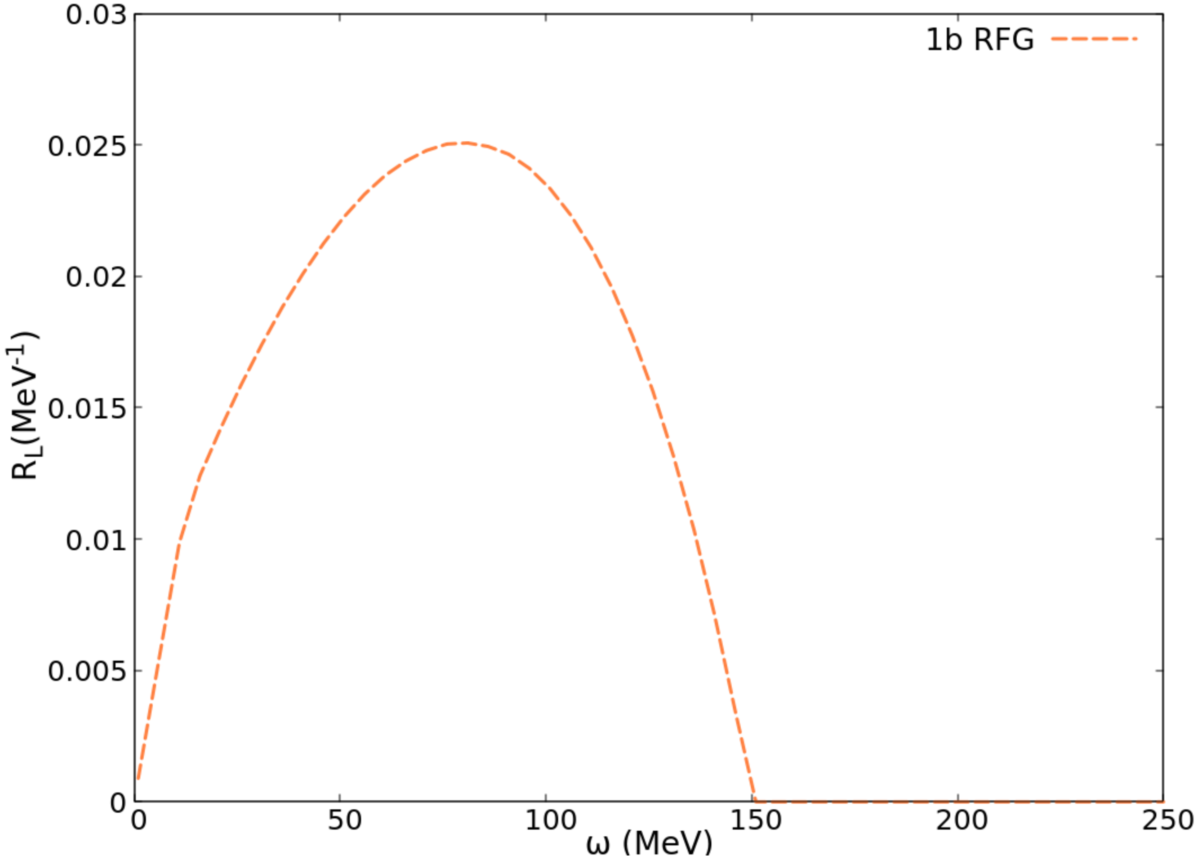
- The **intermediate bound nucleons** are described as **RFG nucleons** with a **modified energy and mass** accounting for the relativistic **interaction of nucleons** with the mean-field potential.

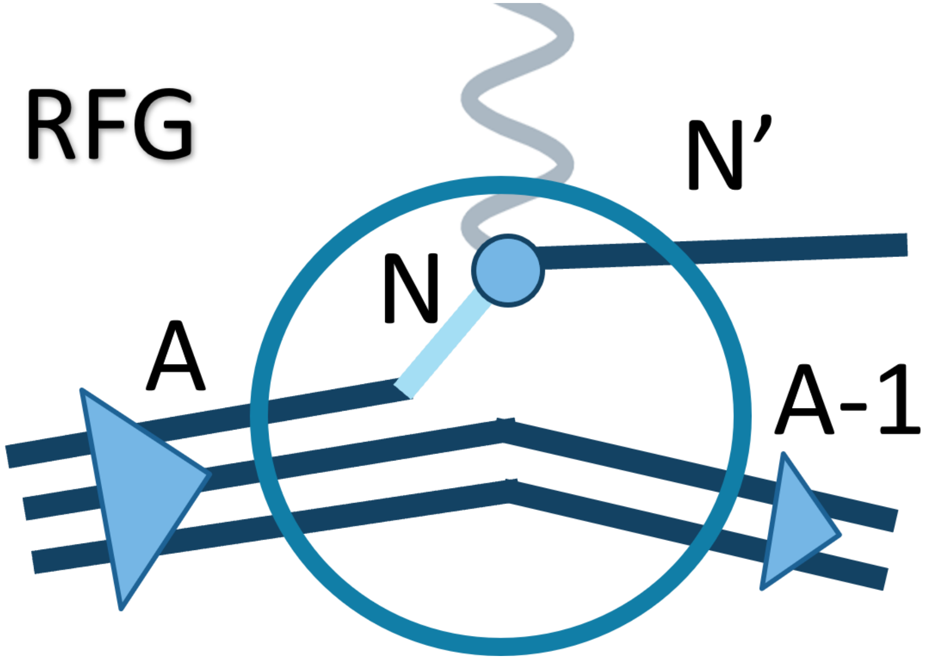
$E^{*} = \sqrt{p^2 + (M^{*})^2} + E_V \qquad M^{*} = \alpha\, M$



Intermediate RFG*-nucleon approximation

- **12C electromagnetic responses (only one-body current)**





Intermediate RFG*-nucleon approximation

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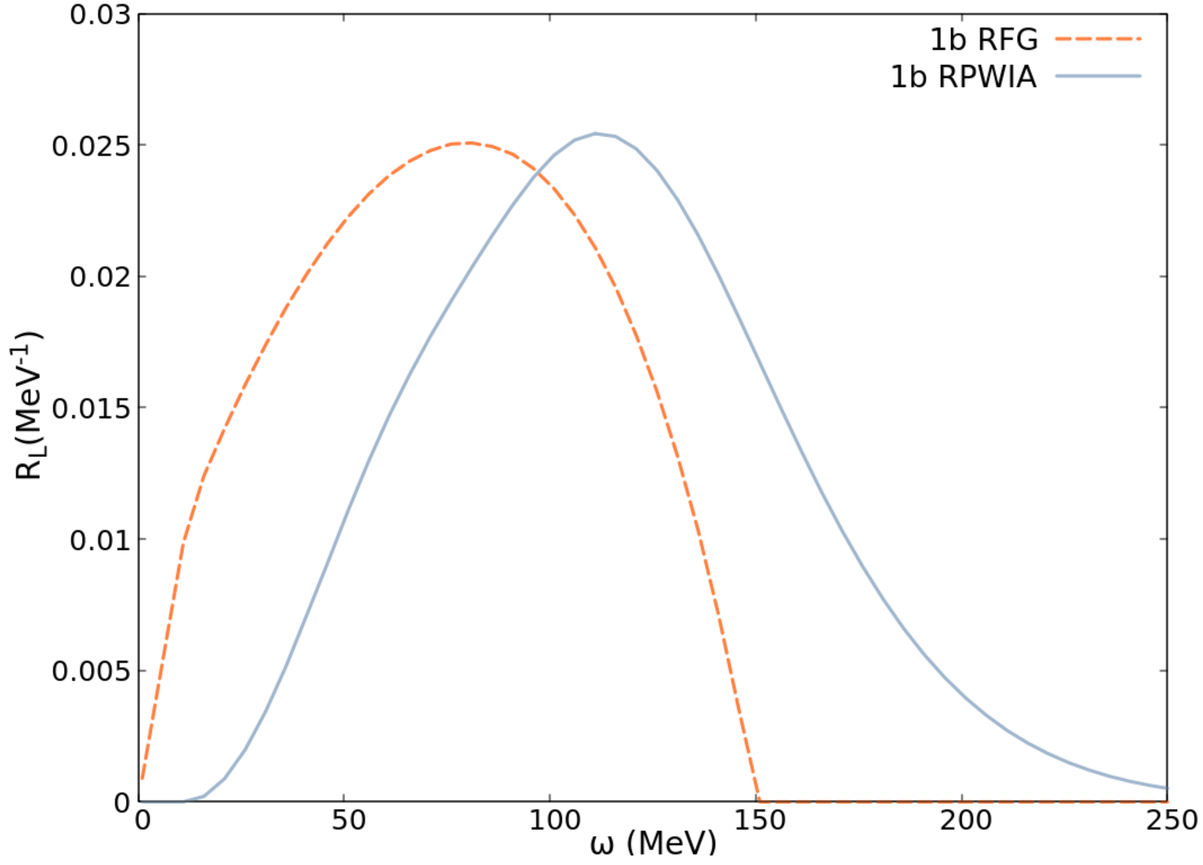

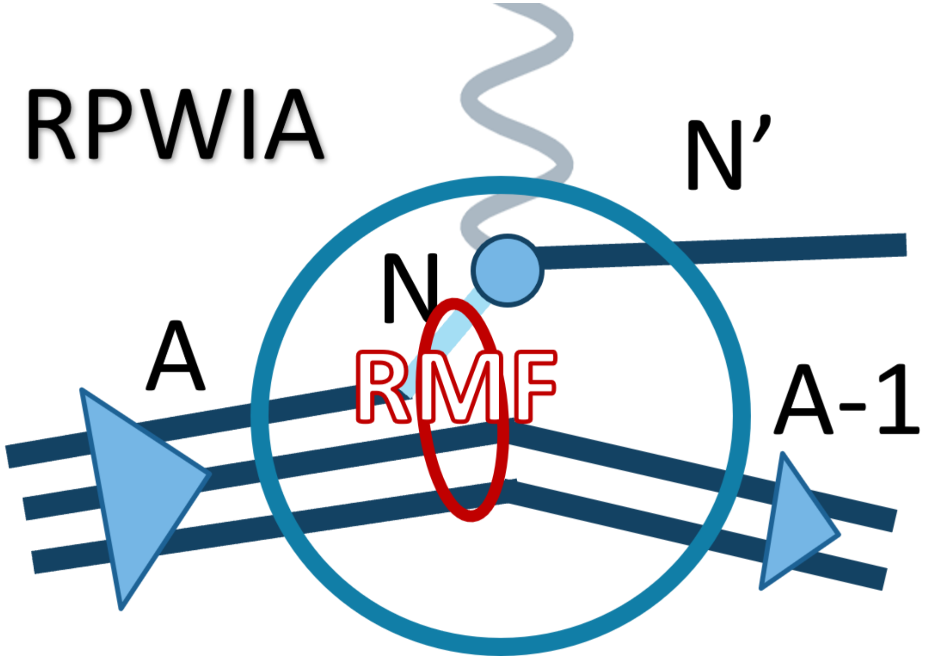

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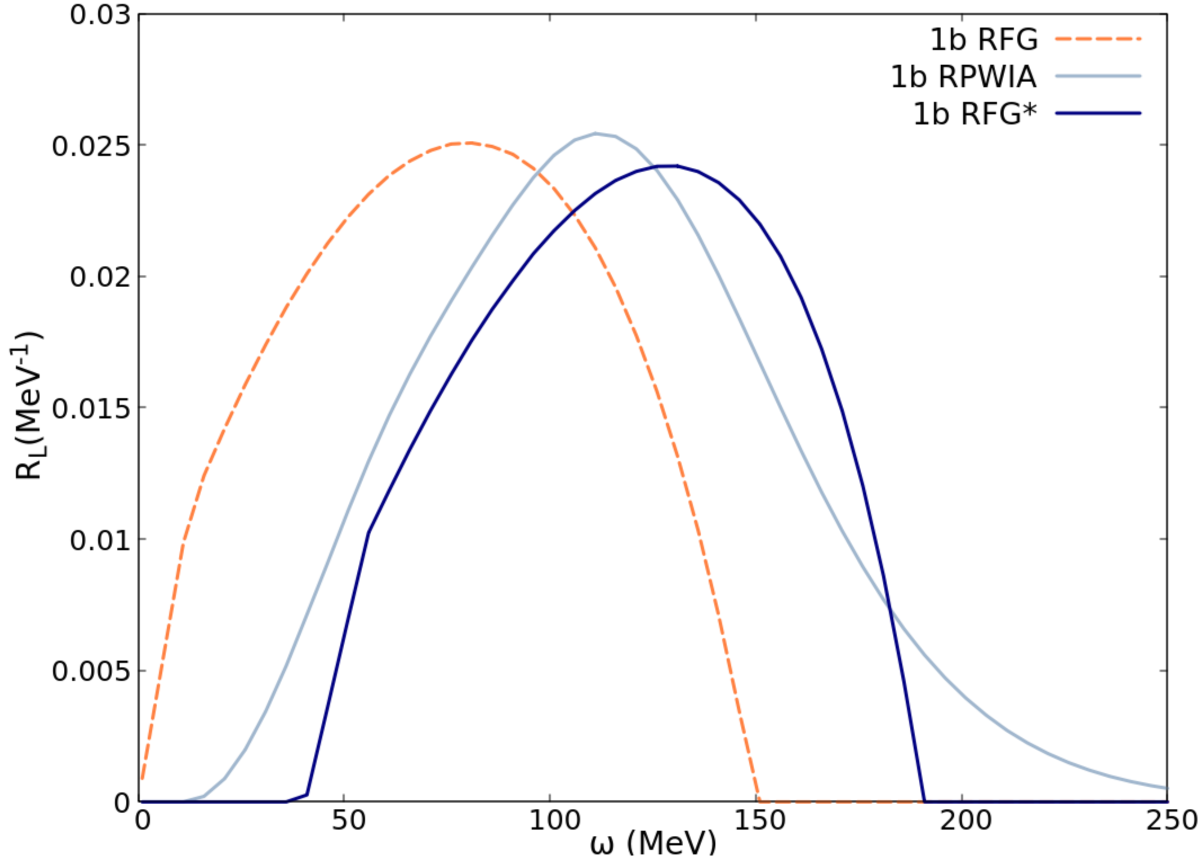
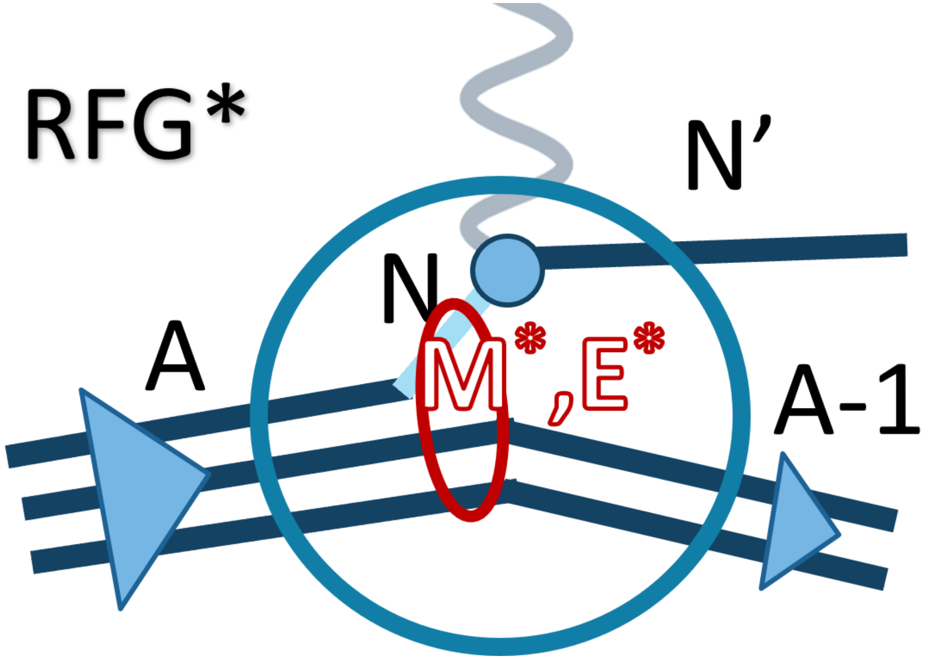
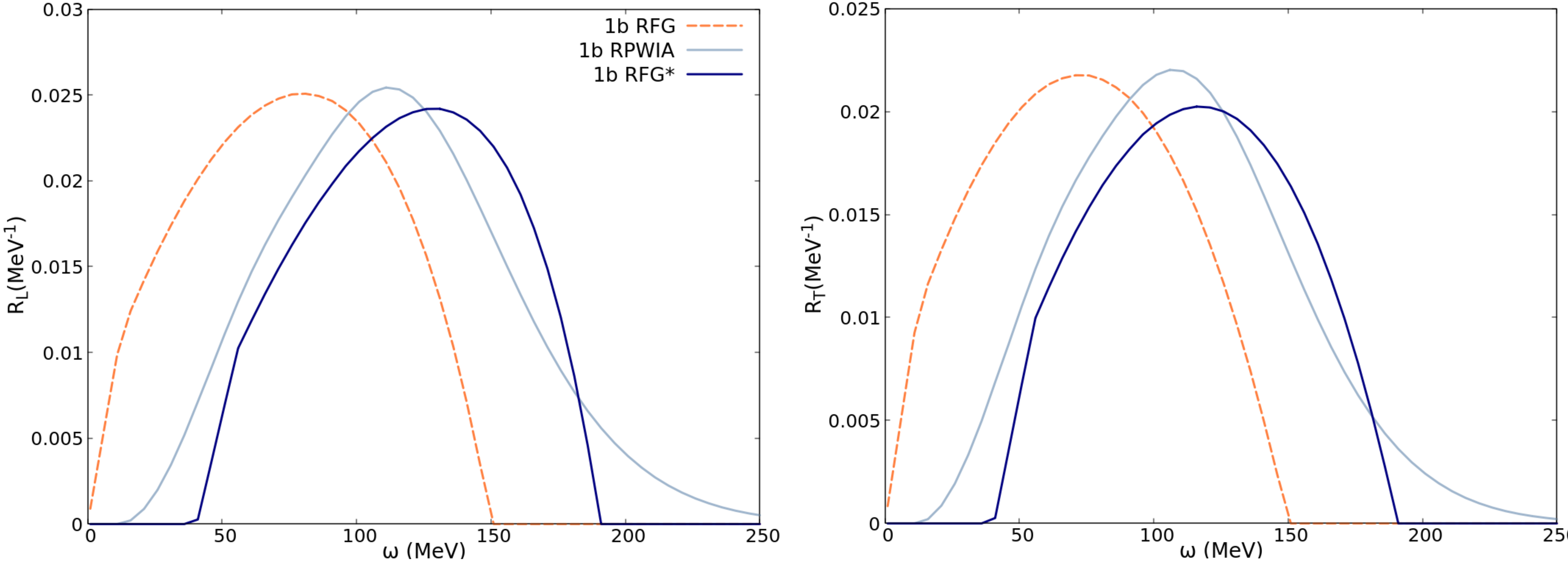




- α=0.8 and E_v=141 MeV for ^{12}C.

Intermediate RFG*-nucleon approximation

- **12C electromagnetic responses (only one-body current)**



- α=0.8 and E_ν=141 MeV for ^{12}C.

Intermediate RFG*-nucleon approximation

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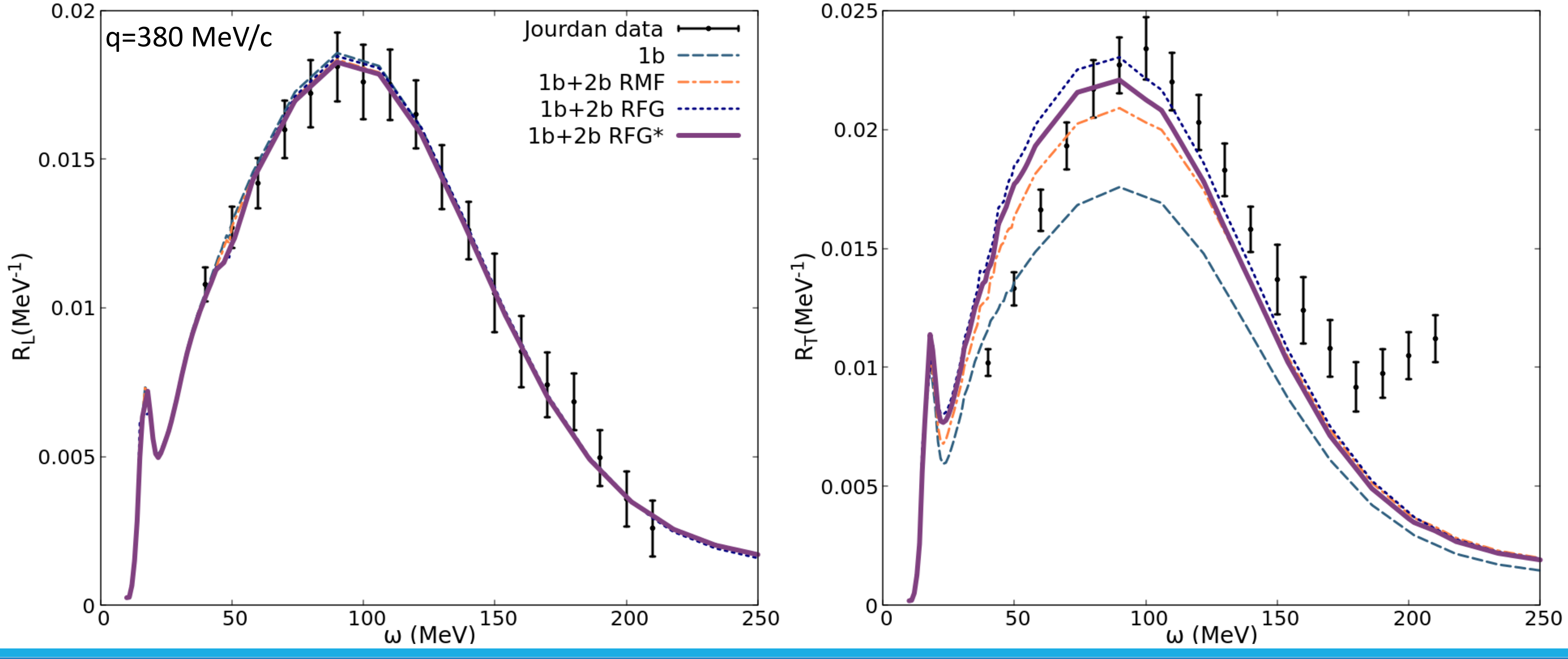
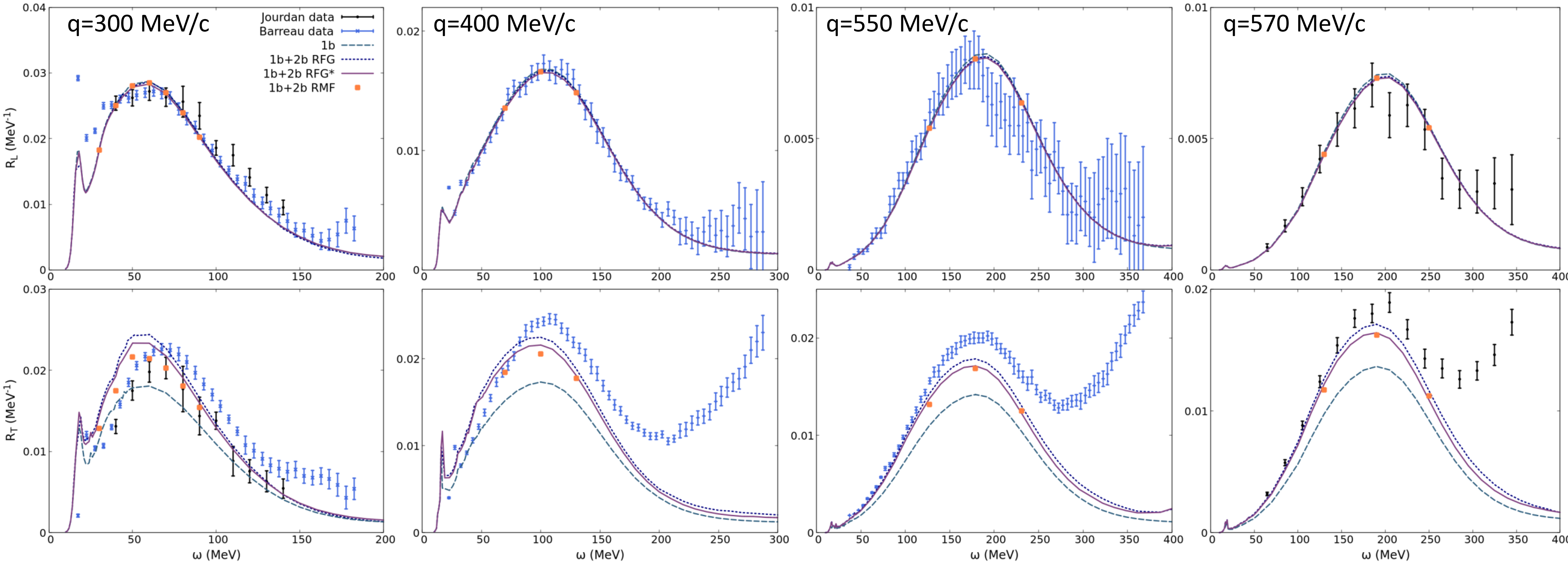
^{12}C electromagnetic inclusive responses



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

^{12}C electromagnetic responses



- Essentially identical RFG* and RMF results for momentum transfer around and above **500 MeV/c**.

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

P. Barreau et al., Nuclear Physics A 402,515 (1983).

Quantum mechanics in the final nucleon

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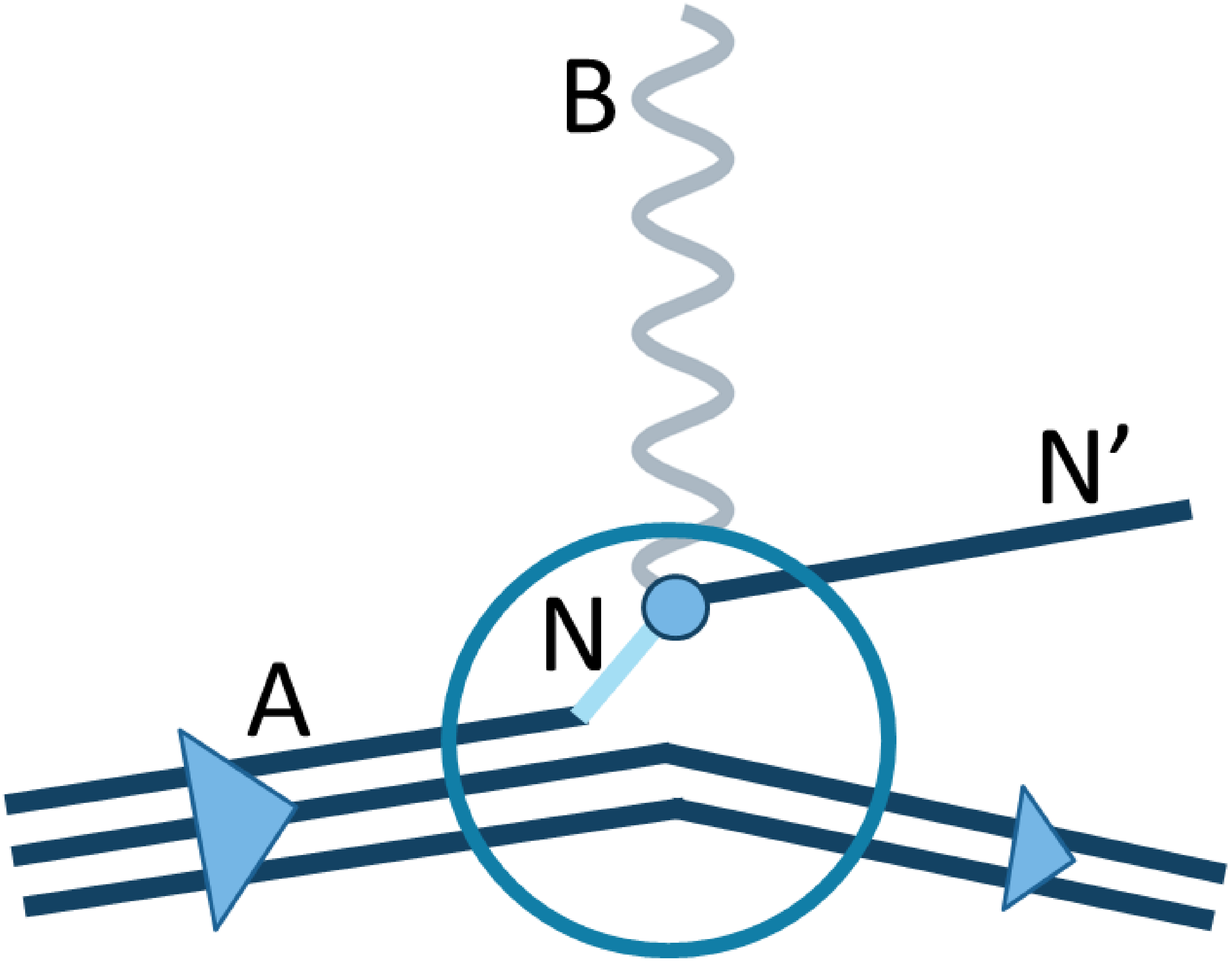
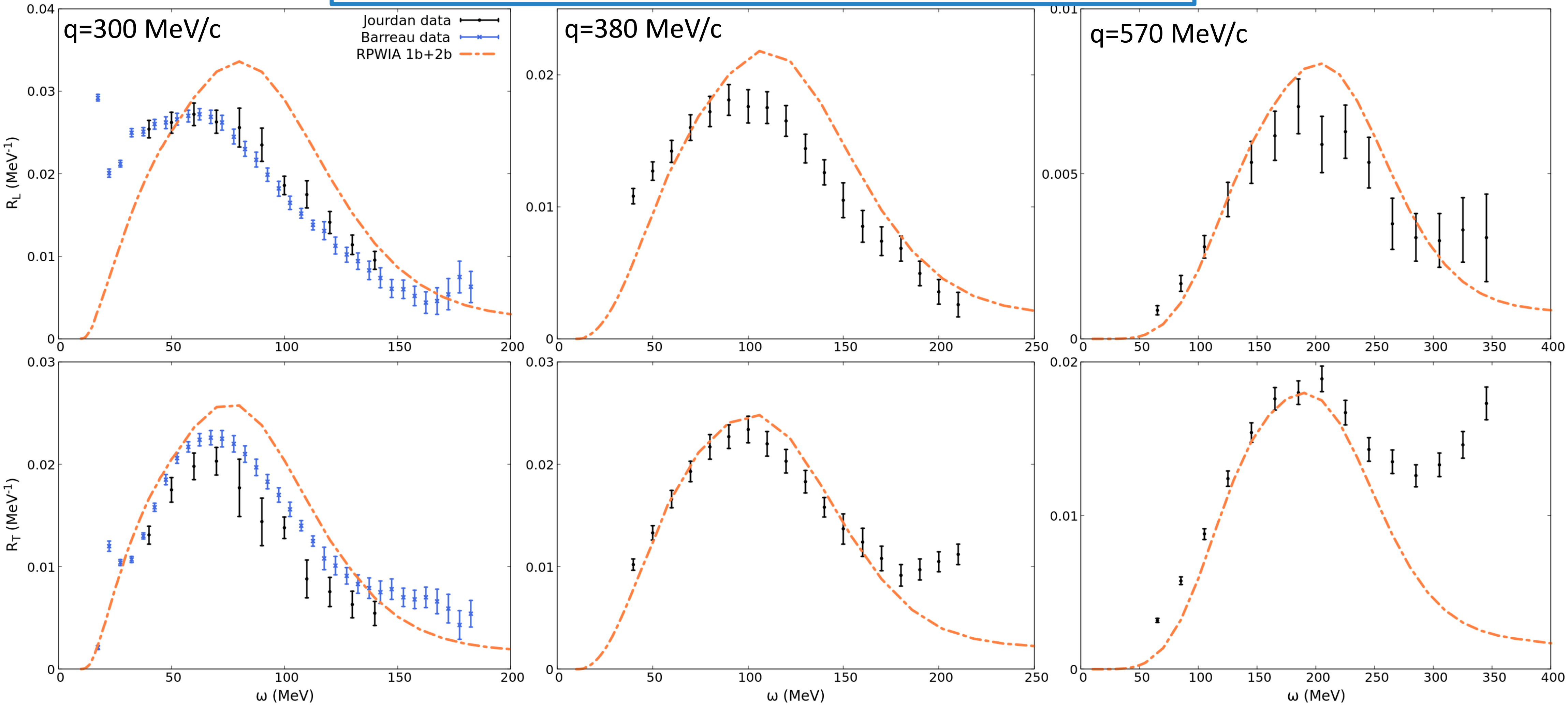
No FSI:
Plane waves



Quantum mechanics in the final nucleon

^{12}C electromagnetic inclusive responses



Quantum mechanics in the final nucleon

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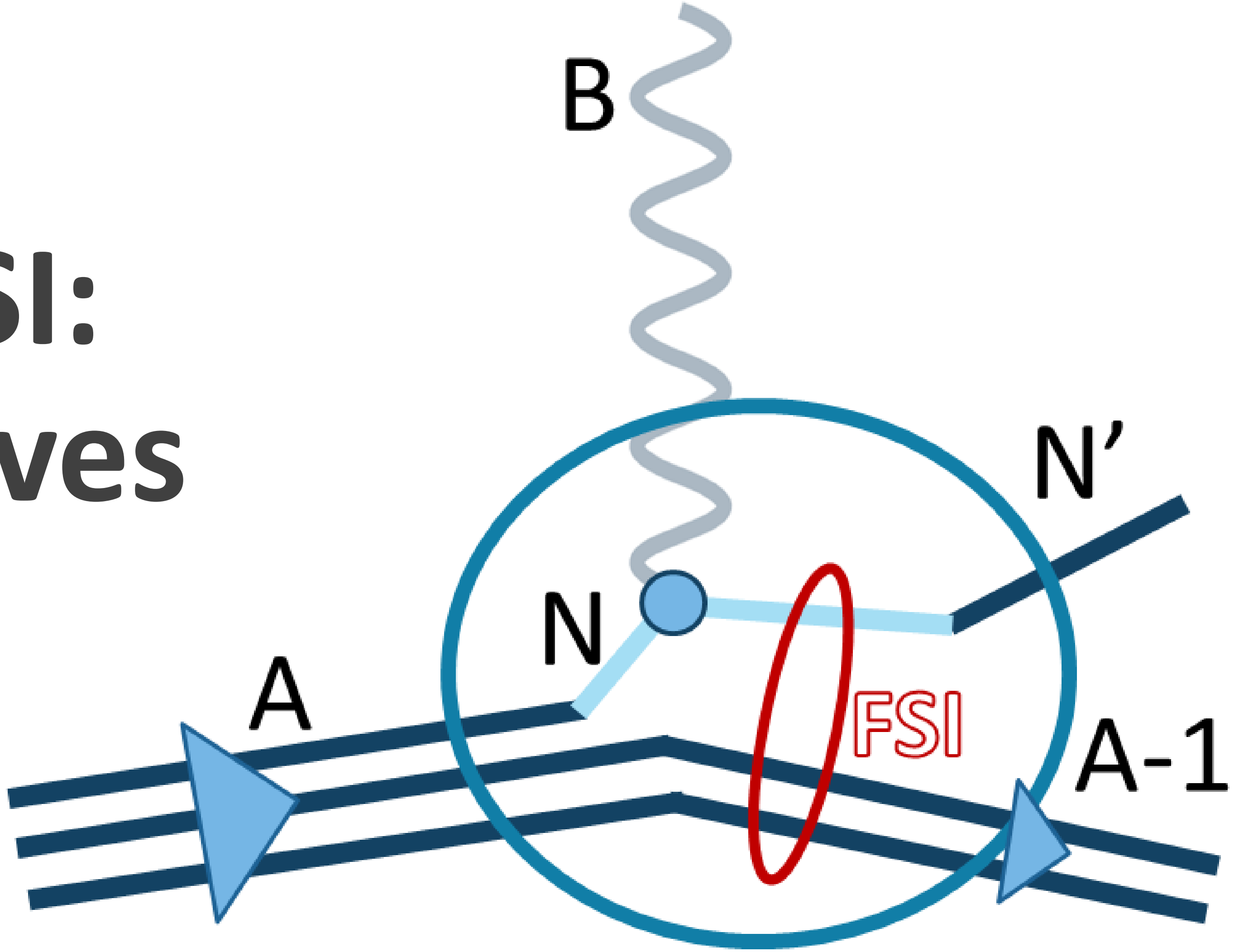
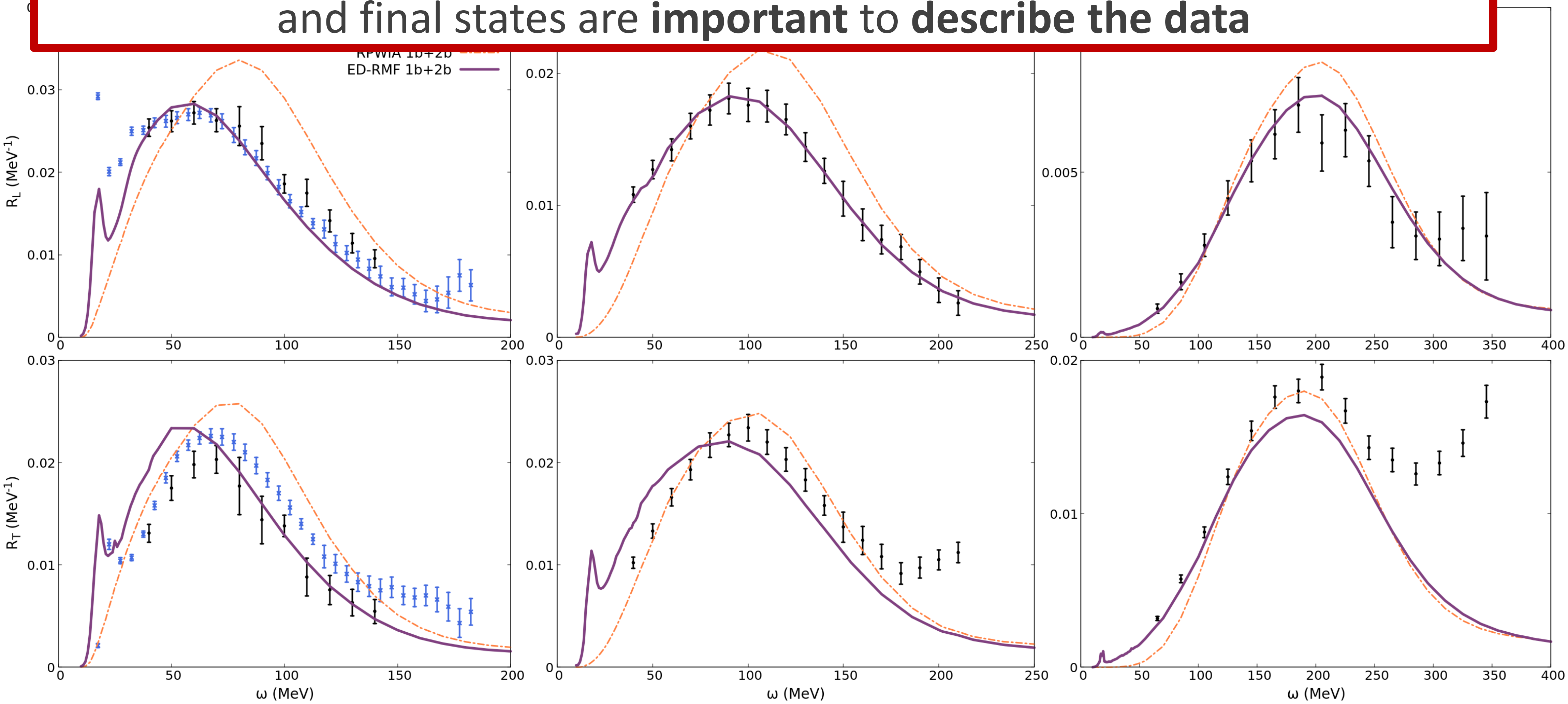
Including FSI: Distorted waves



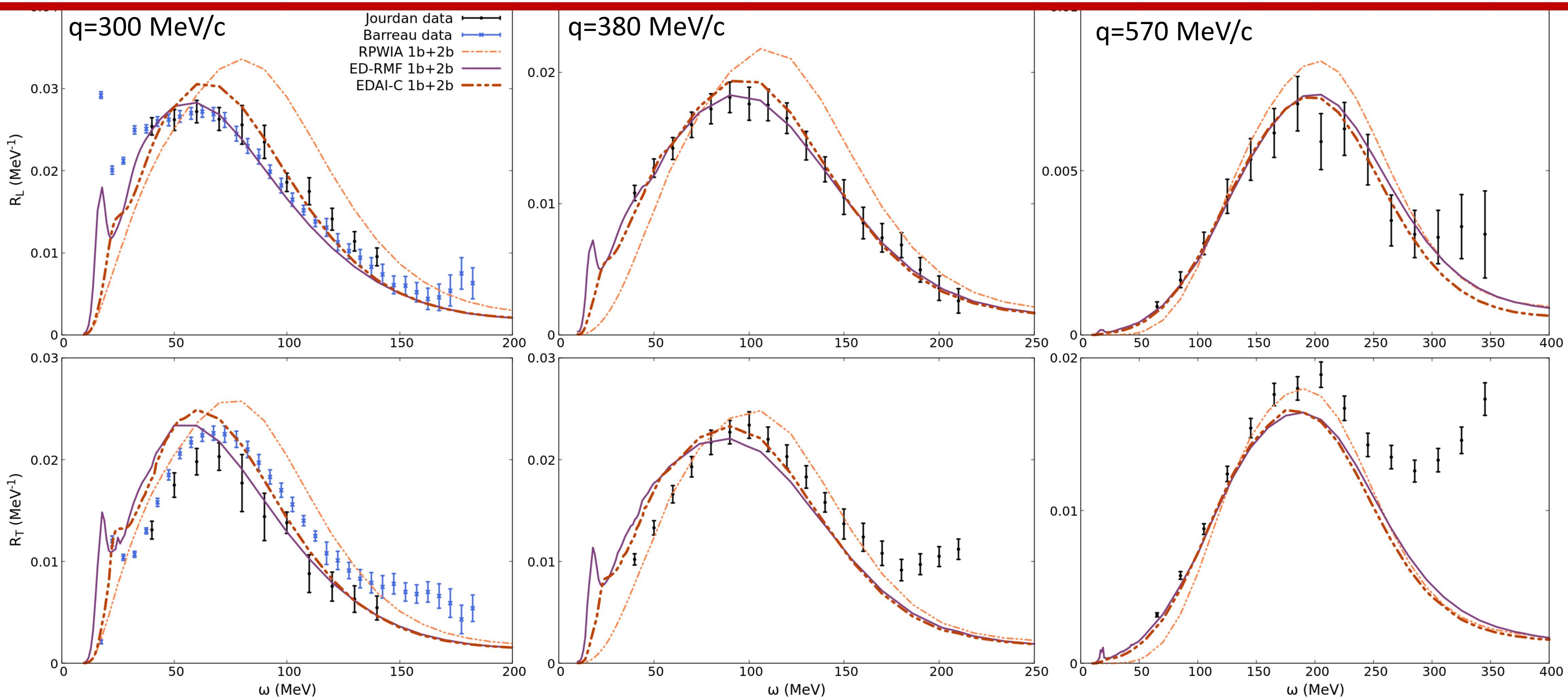
Quantum mechanics in the final nucleon

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



Quantum mechanics in the final nucleon

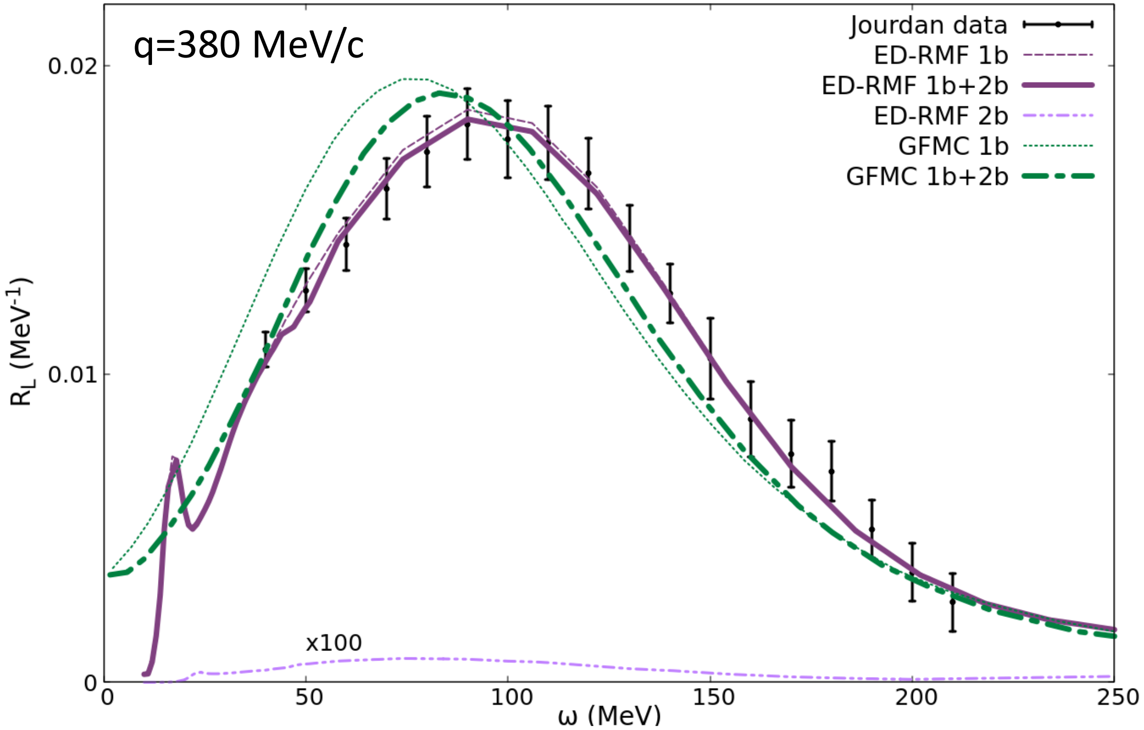
Spurious contributions appear from **non-orthogonality** between initial and final states

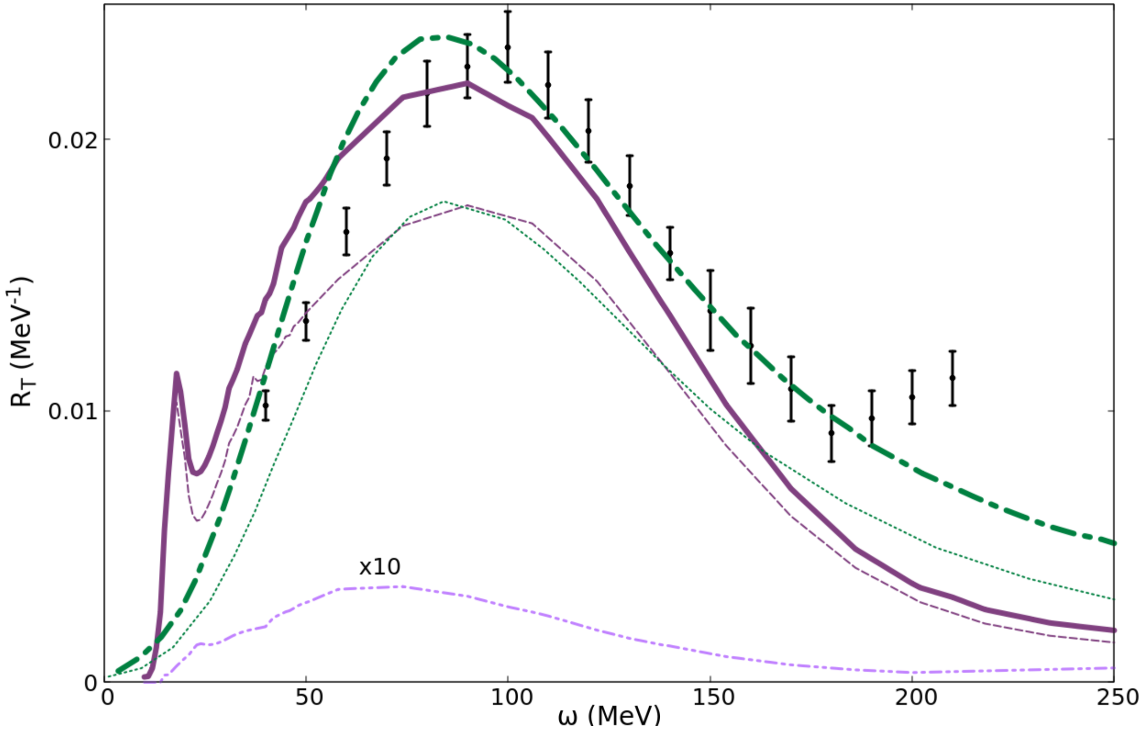


EDAI-C: E. D. Cooper, S. Hama, B. C. Clark, and R. L. Mercer, Phys. Rev. C 47, 297 (1993).

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**



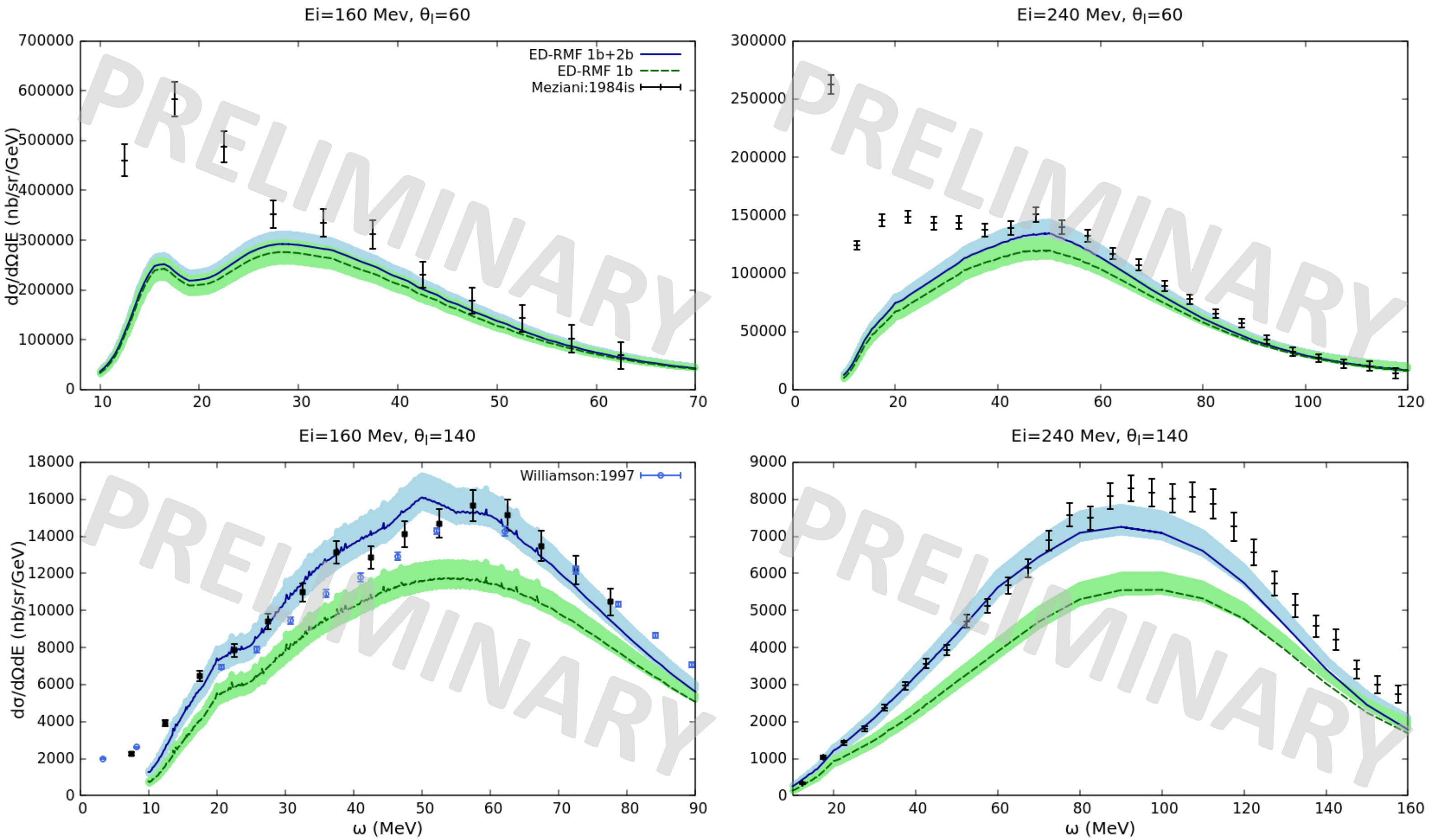


GFMC: A. Lovato, S. Gandolfi, J. Carlson, S. C. Pieper, and R. Schiavilla, Phys. Rev. Lett. 117, 082501 (2016).

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

^{40}Ca inclusive cross section

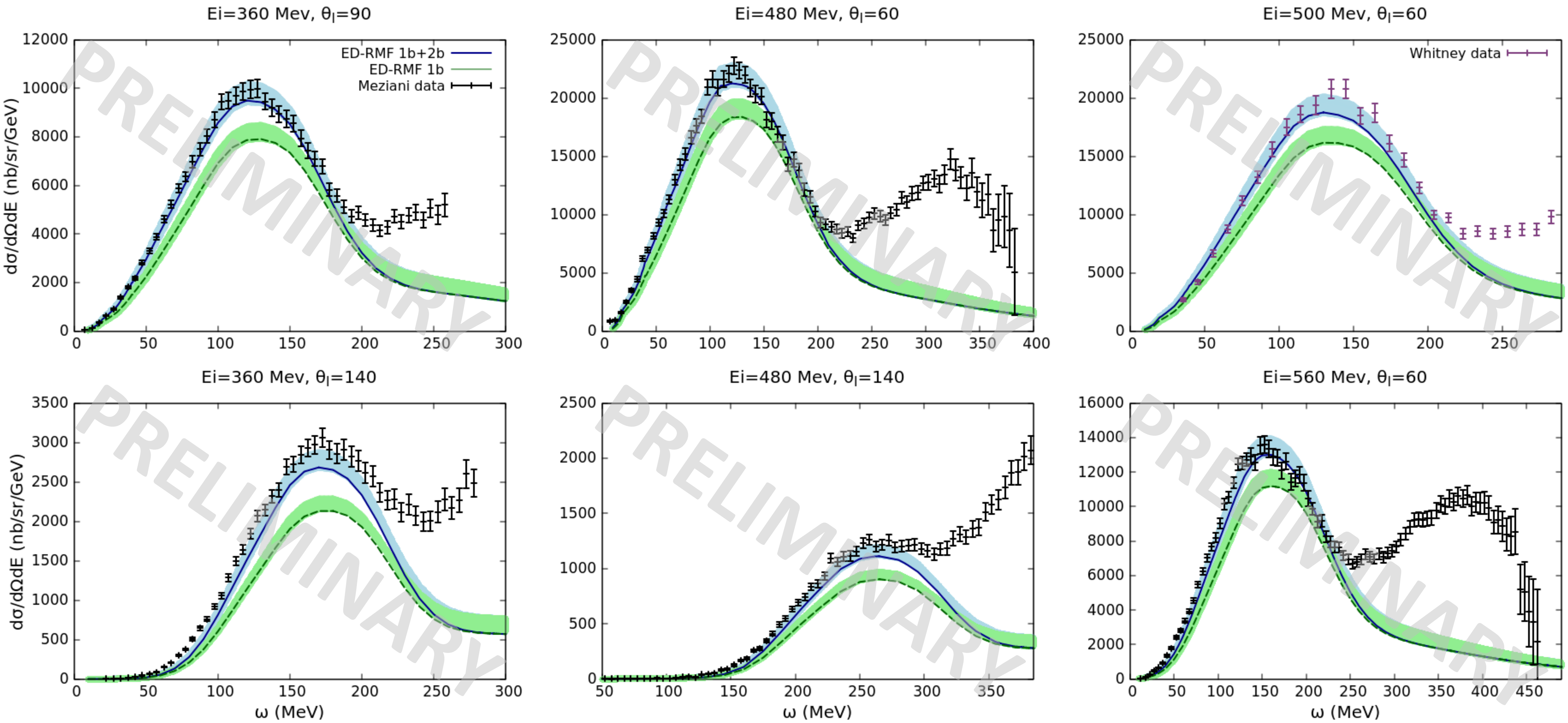
- The relativistic and quantum mechanical treatment of the process allows its application to heavier nuclei.



Shell model state	Occupation probability
$1d_{3/2}+2s_{1/2}$	0.61 ± 0.04
$1d_{3/2}$	0.65 ± 0.05
$2s_{1/2}$	0.53 ± 0.04
$1d_{5/2}$	0.85 ± 0.09
$1p_{3/2}+1p_{1/2}$	0.49 ± 0.07
$1s_{1/2}$	0.89 ± 0.09

40Ca occupations: Y. Yasuda, Ph.D. thesis, Kyoto University (2012).
Data: discovery.phys.virginia.edu/research/groups/qes-archive/data/40Ca.html

^{40}Ca inclusive cross section



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 which **can simultaneously describe the longitudinal and transverse electromagnetic responses** of ^{12}C in the quasielastic regime.

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  - Different approaches to describe the intermediate bound-nucleon state of the two-body currents have been studied → **the RFG* approach resulted as an excellent approximation to the complete model**.

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- After the success of the model in the scrutiny against electron scattering data, it can be applied to **neutrino-nucleus interaction**.

Thanks for your attention !