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Grupo de Física Nuclear

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AGENCIA ESTATAL DE INVESTIGACIÓN

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Meson exchange currents in one-nucleon knockout within a relativistic mean-field model

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

NuInt 2024 – 14th International Workshop on Neutrinos-Nucleus Interactions

Reference paper

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

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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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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]

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DOI: 10.1103/PhysRevC.108.064608

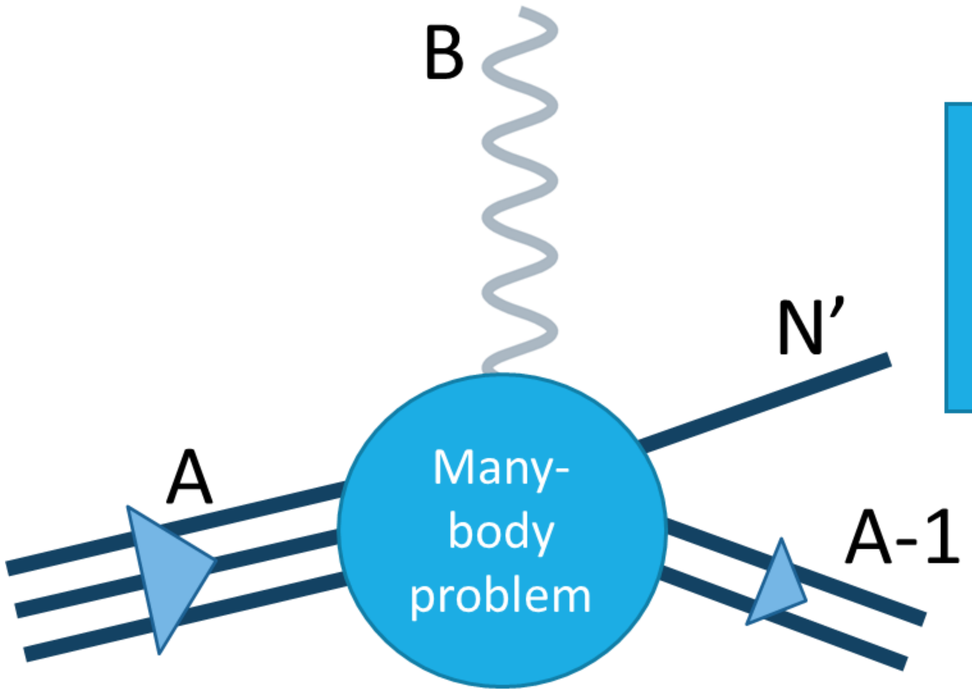
Outline

- **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
  - ^{40}Ca inclusive responses and cross section
- **Neutrino-nucleus scattering**
  - ^{12}C inclusive responses and cross section
- Conclusions and future prospects

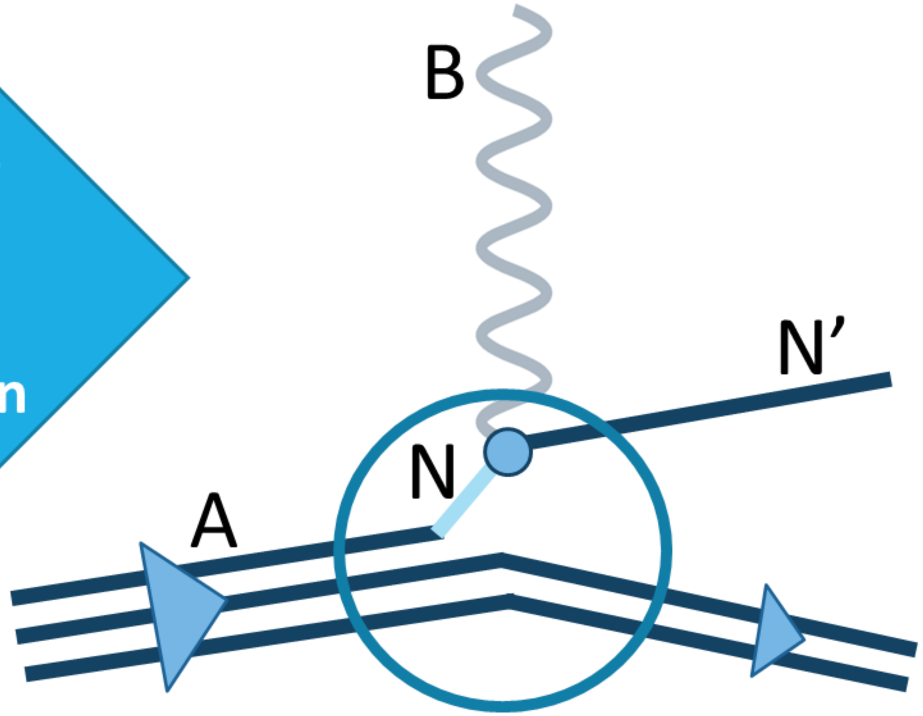
Outline

- **Theoretical framework**

Quasielastic scattering



Independent Particle Shell Model + Impulse Approximation



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

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

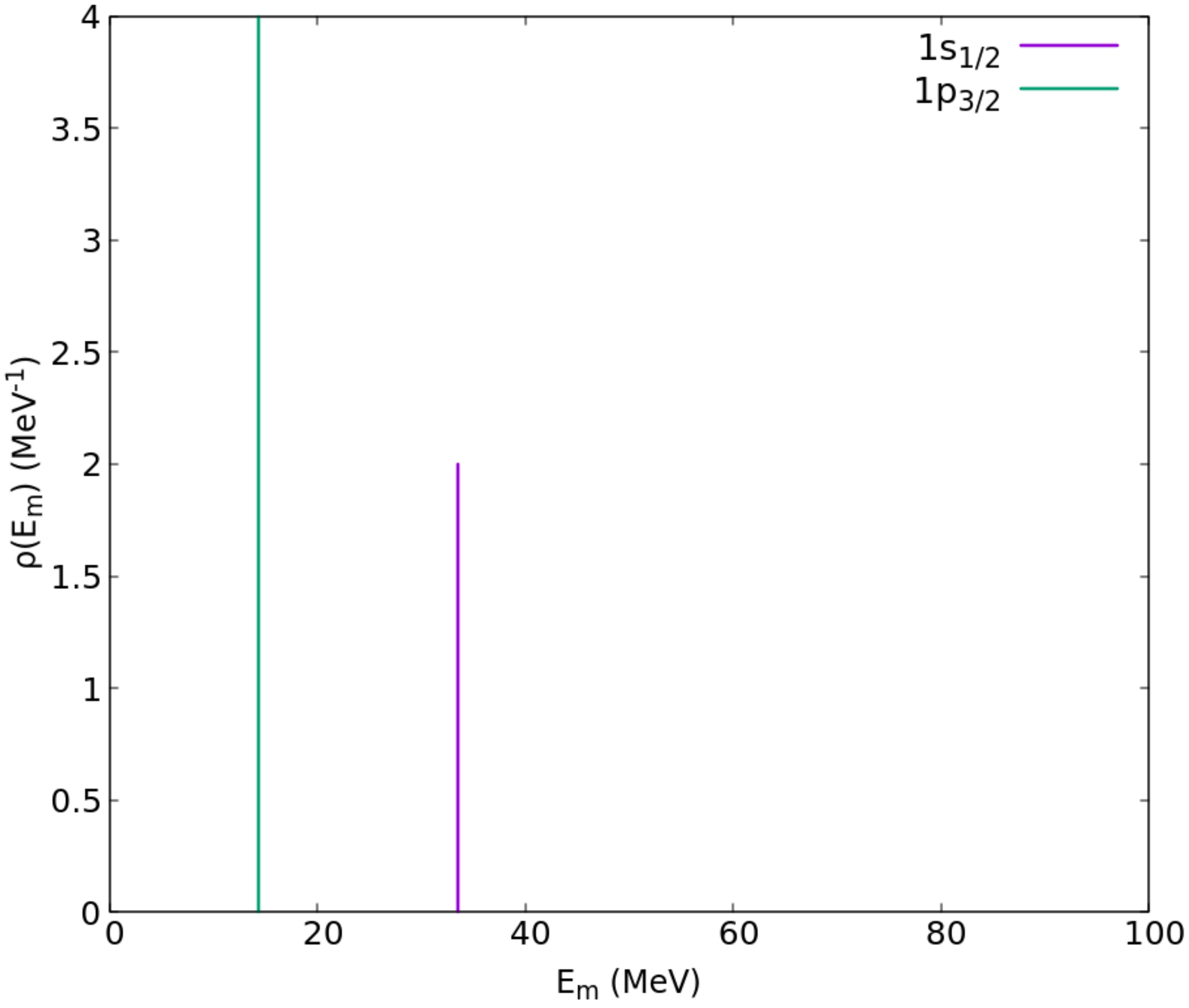
Outline

- 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**

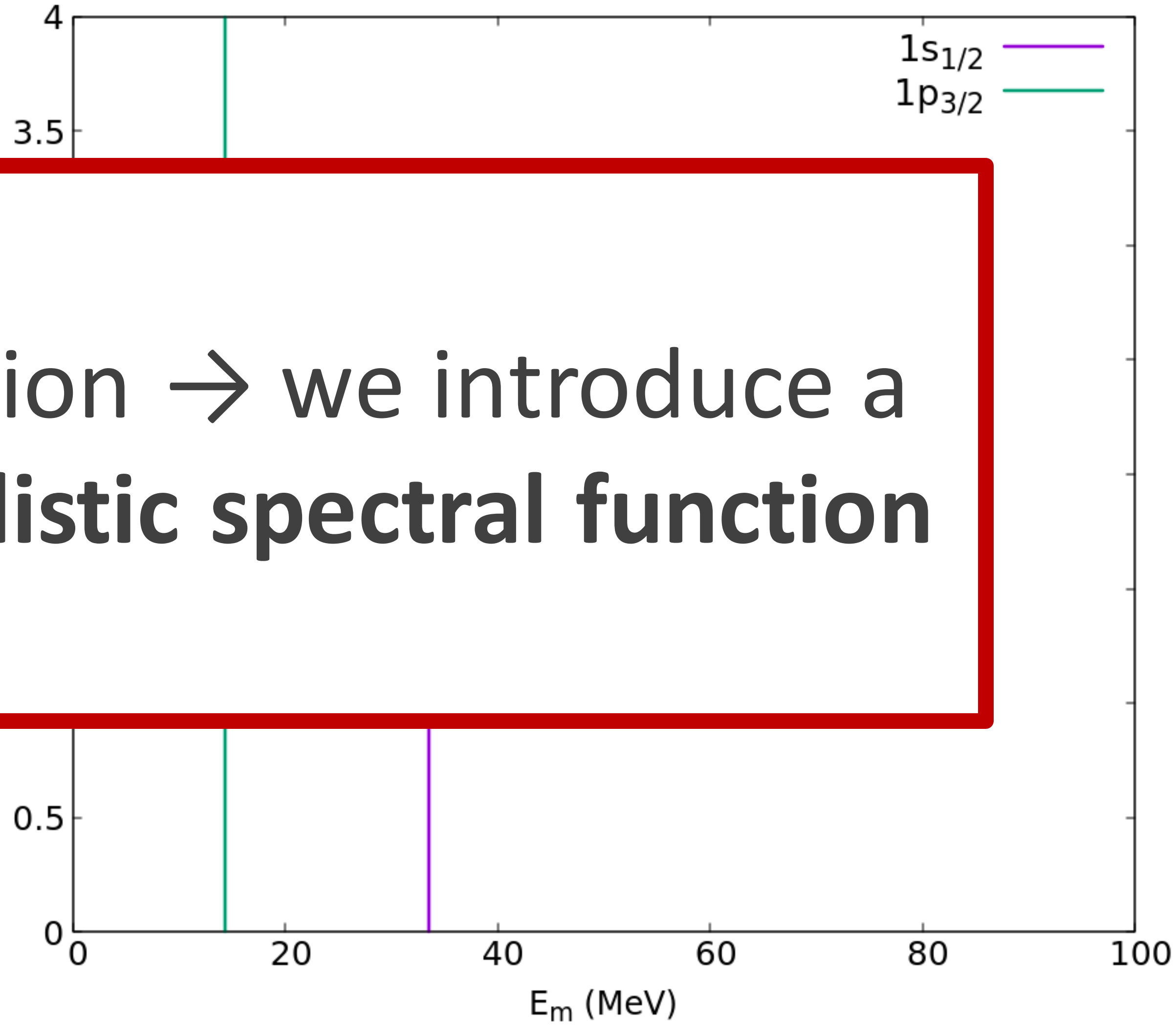
$$\rho(E_m) = \sum_{\kappa} N_\kappa \, \delta(E_m - E_{m,\kappa})$$



^{12}C independent particle shell model

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

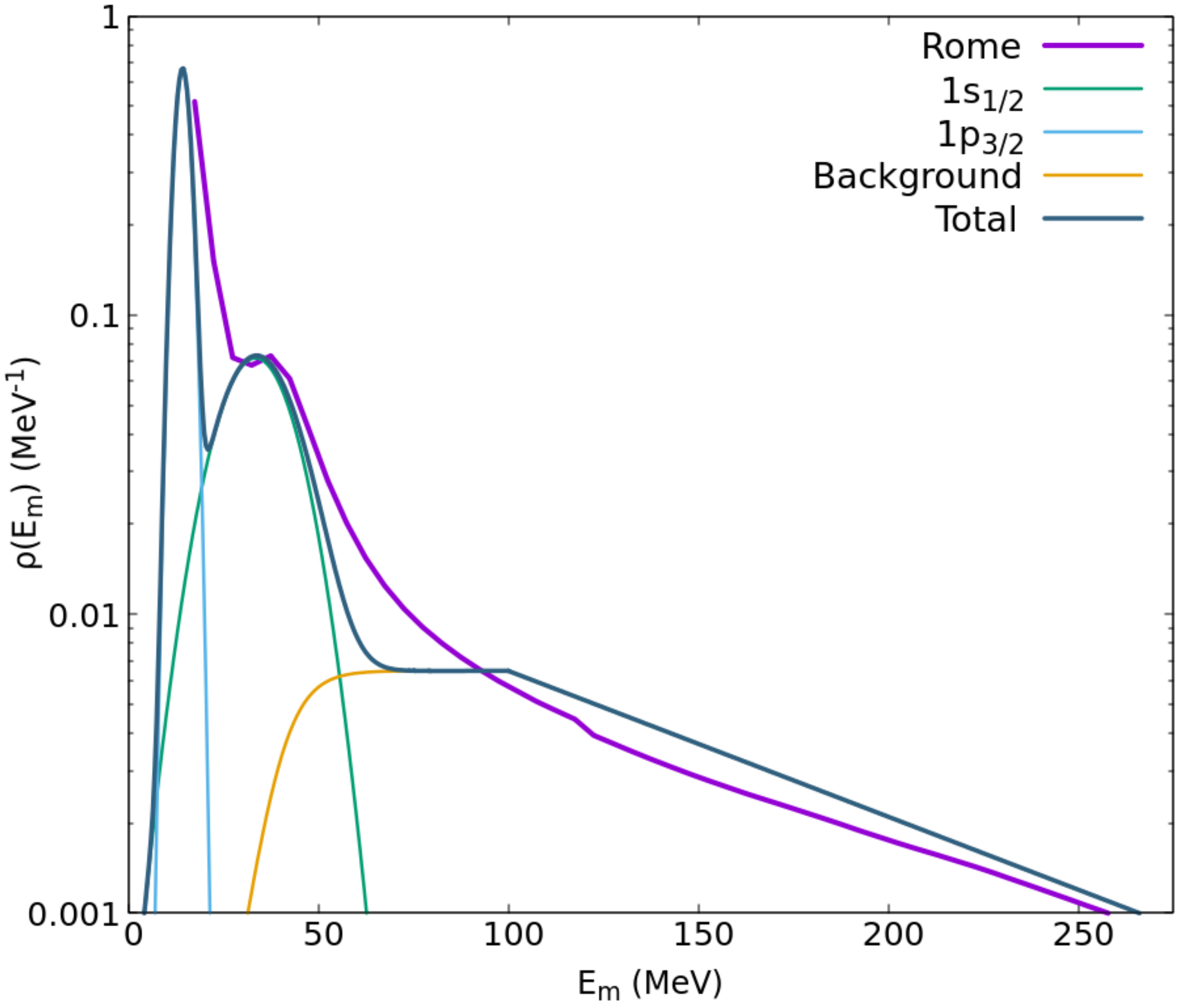
$$\rho(E_m) = \sum_{\kappa} N_\kappa\, \delta(E_m - E_{m,\kappa})$$



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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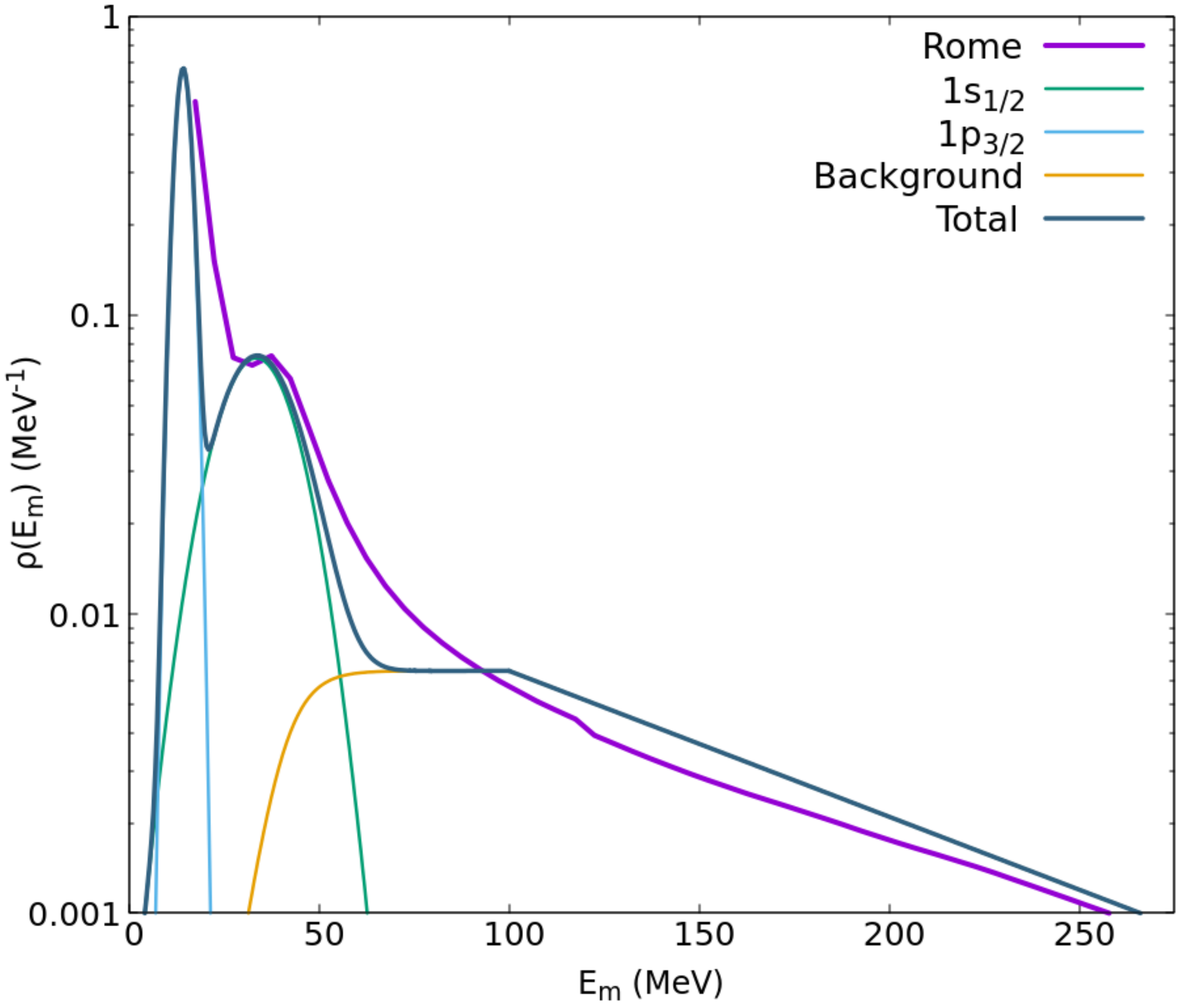
    - 3.3 nucleons in $1p_{3/2}$
  - **Continuous missing energy profile**



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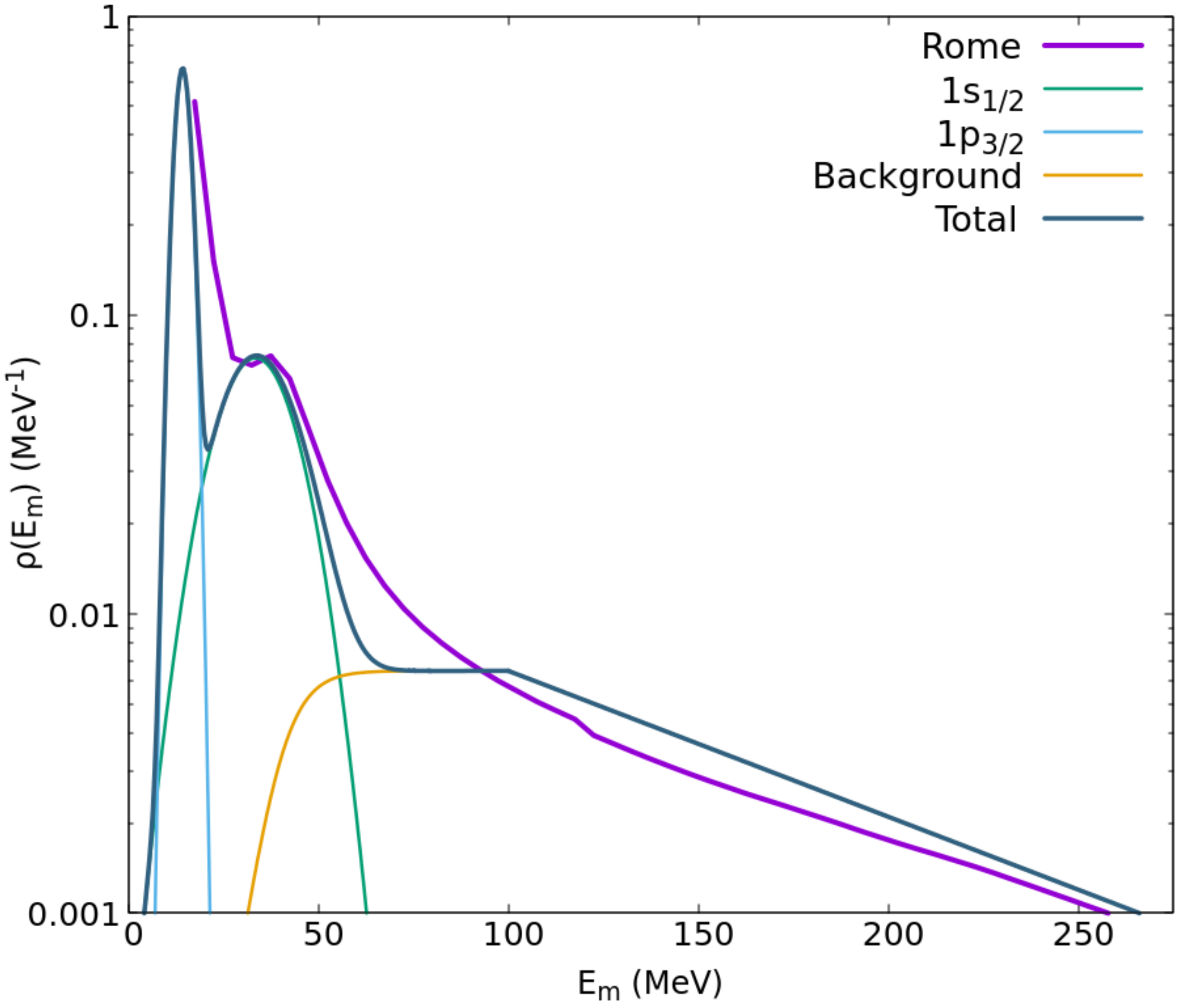
  - Continuous missing energy profile
  - **Background due to short range correlations**
    - 0.9 nucleons



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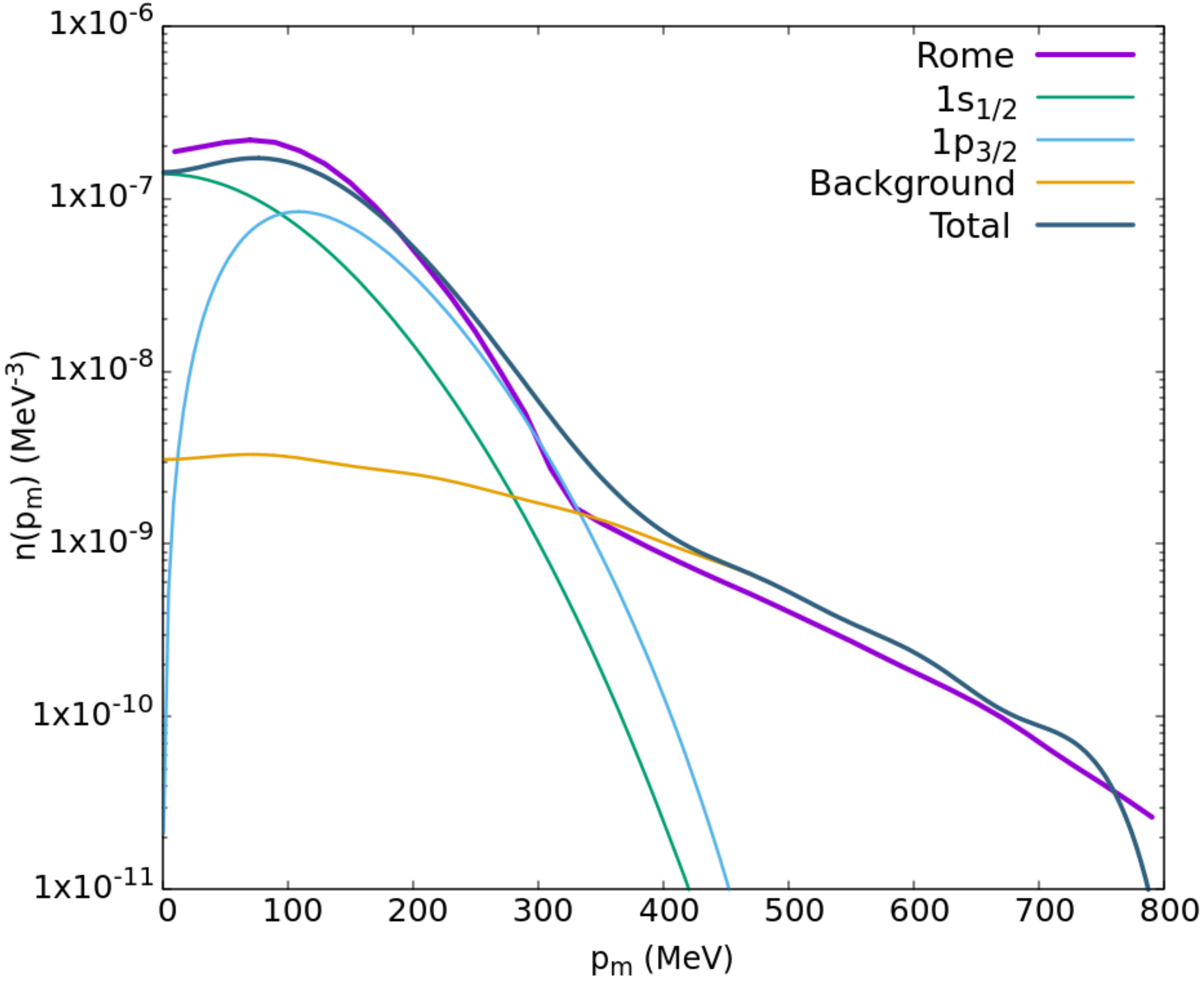


Rome Spectral Function: O. Benhar et al., Nuclear Physics A 579, 493 (1994).

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

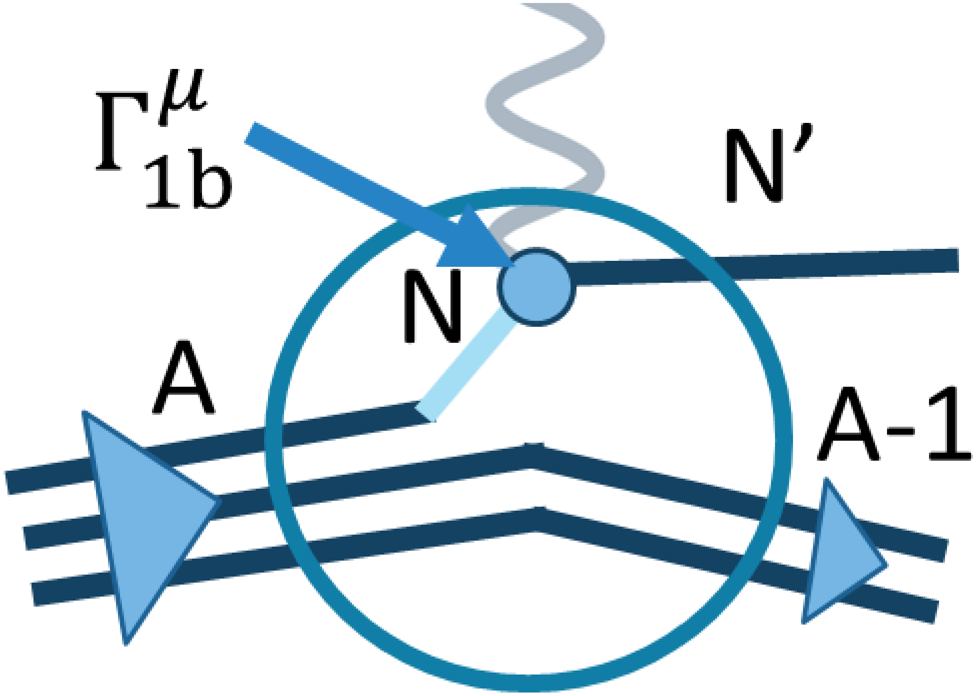
$$J^{\mu}_{had} \sim \bar{\Psi}^{s}(\boldsymbol{p}'_N, \boldsymbol{p}_N)\, \Gamma^{\mu}\, \Psi^{\kappa}_{m_j}(\boldsymbol{p})$$

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

Hadronic current operator

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

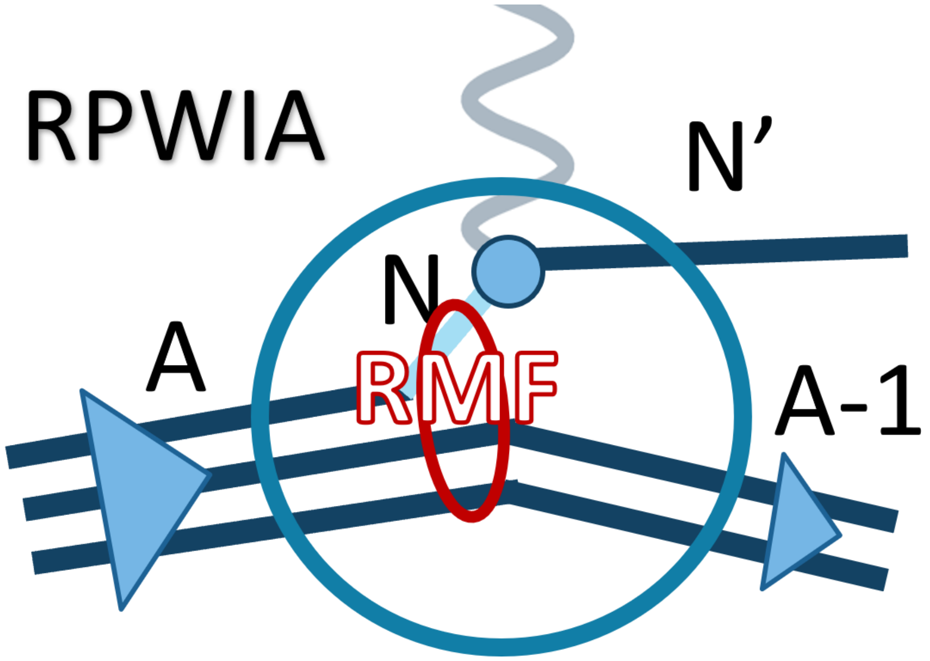
- **Hadronic current operator**: includes all the processes that lead to a final 1p-1h state.
- In the **impulse approximation**, it corresponds to the **1-body** current operator.



Initial bound nucleon

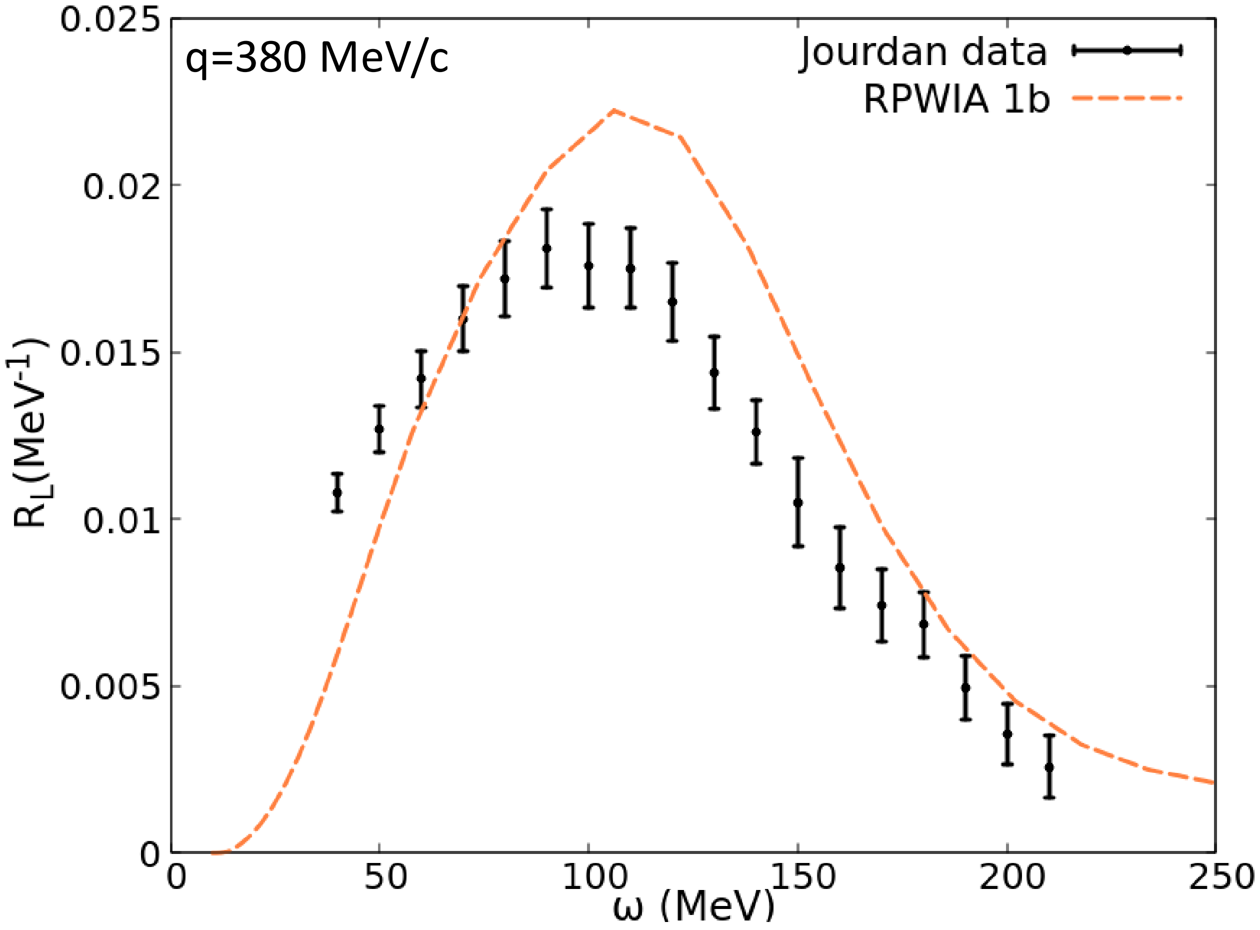
$$J^{\mu}_{had} \sim \overline{\Psi}^{s}(\boldsymbol{p}'_N, \boldsymbol{p}_N)\, \Gamma^{\mu}_{1b}\, \Psi^{\kappa}_{m_j}(\boldsymbol{p})$$

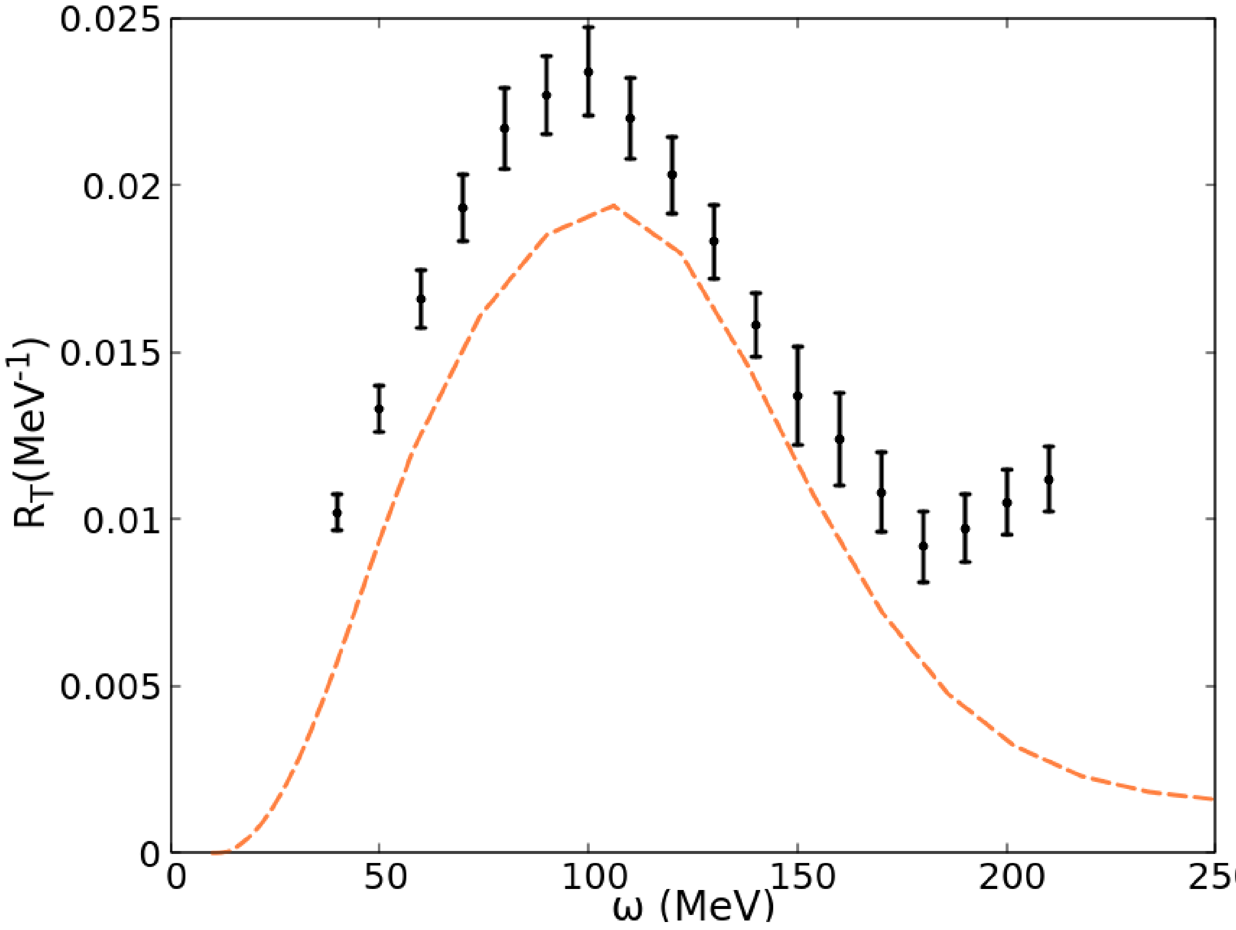
- **Initial nucleon**: bound wave function within the relativistic mean-field (RMF) model.



Initial bound nucleon

^{12}C electromagnetic inclusive responses



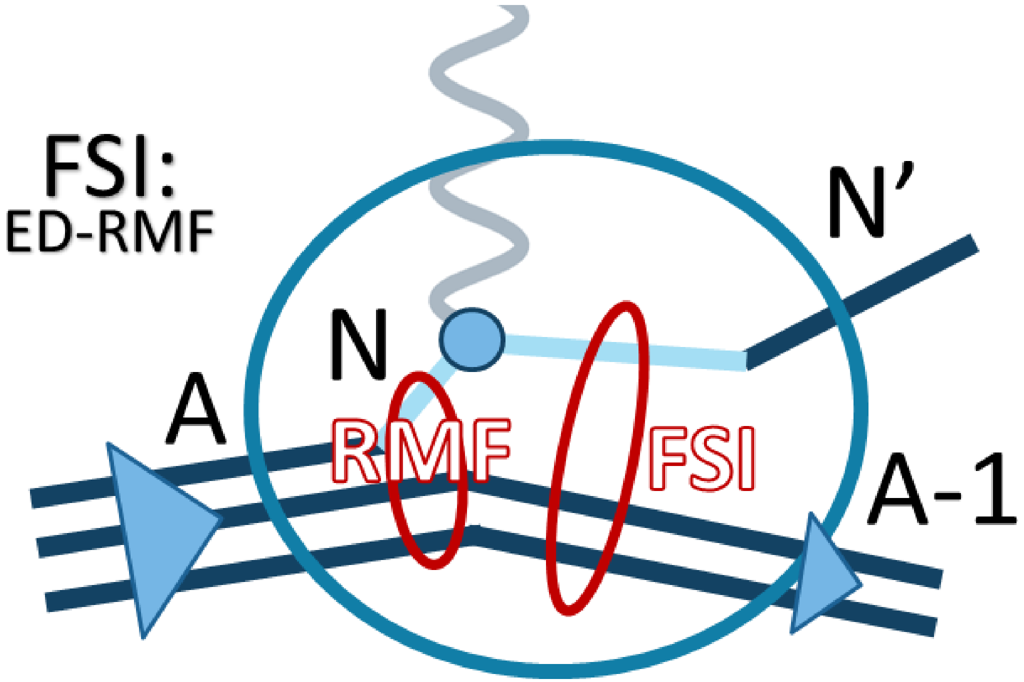


J. Jourdan, Nucl. Phys. A 603, 117 (1996).

Knocked out nucleon

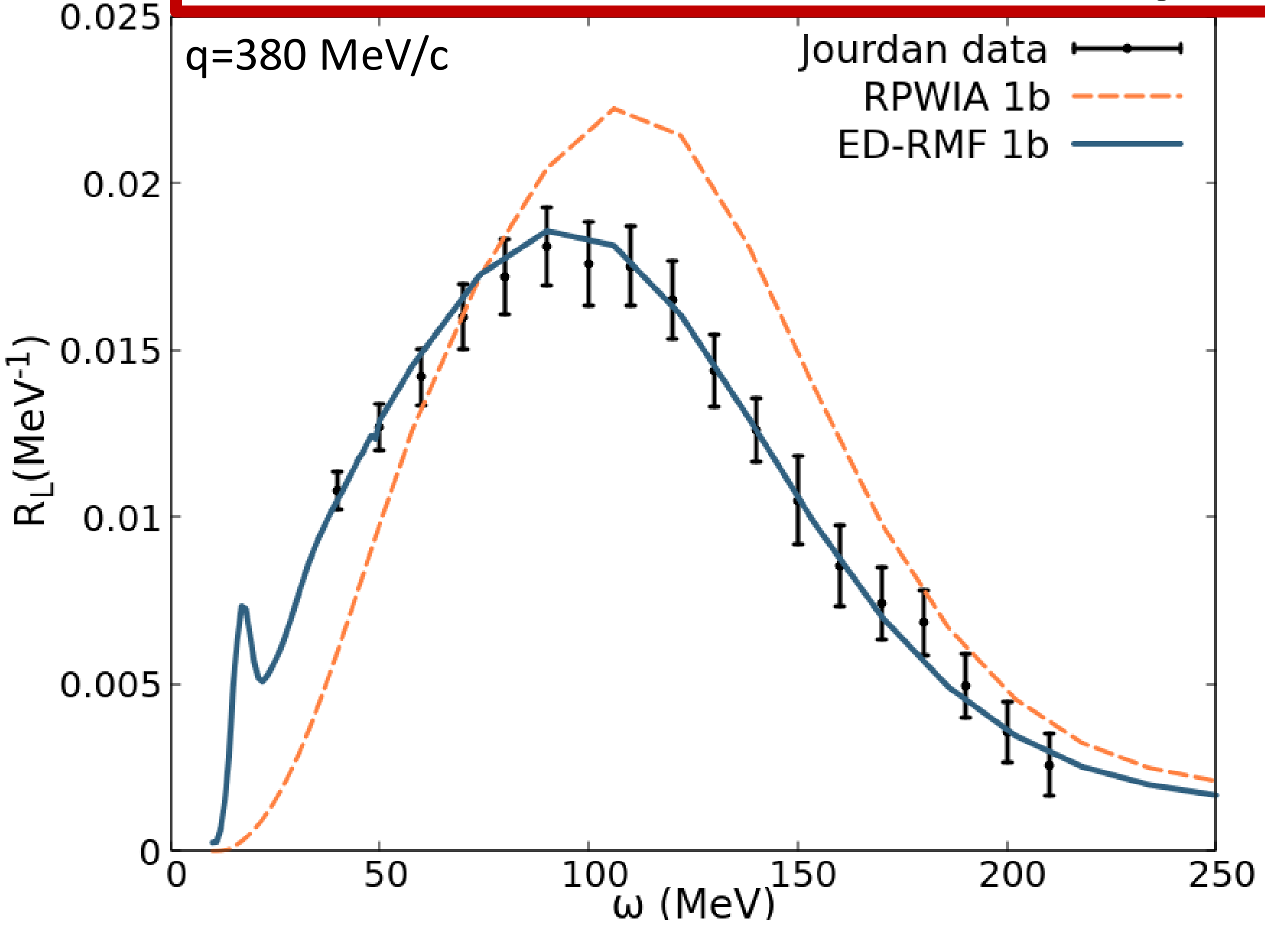
$$J^{\mu}_{had} \sim \overline{\Psi}^{s}(\boldsymbol{p}'_N, \boldsymbol{p}_N)\, \Gamma^{\mu}_{1\mathrm{b}}\, \Psi^{\kappa}_{m_j}(\boldsymbol{p})$$

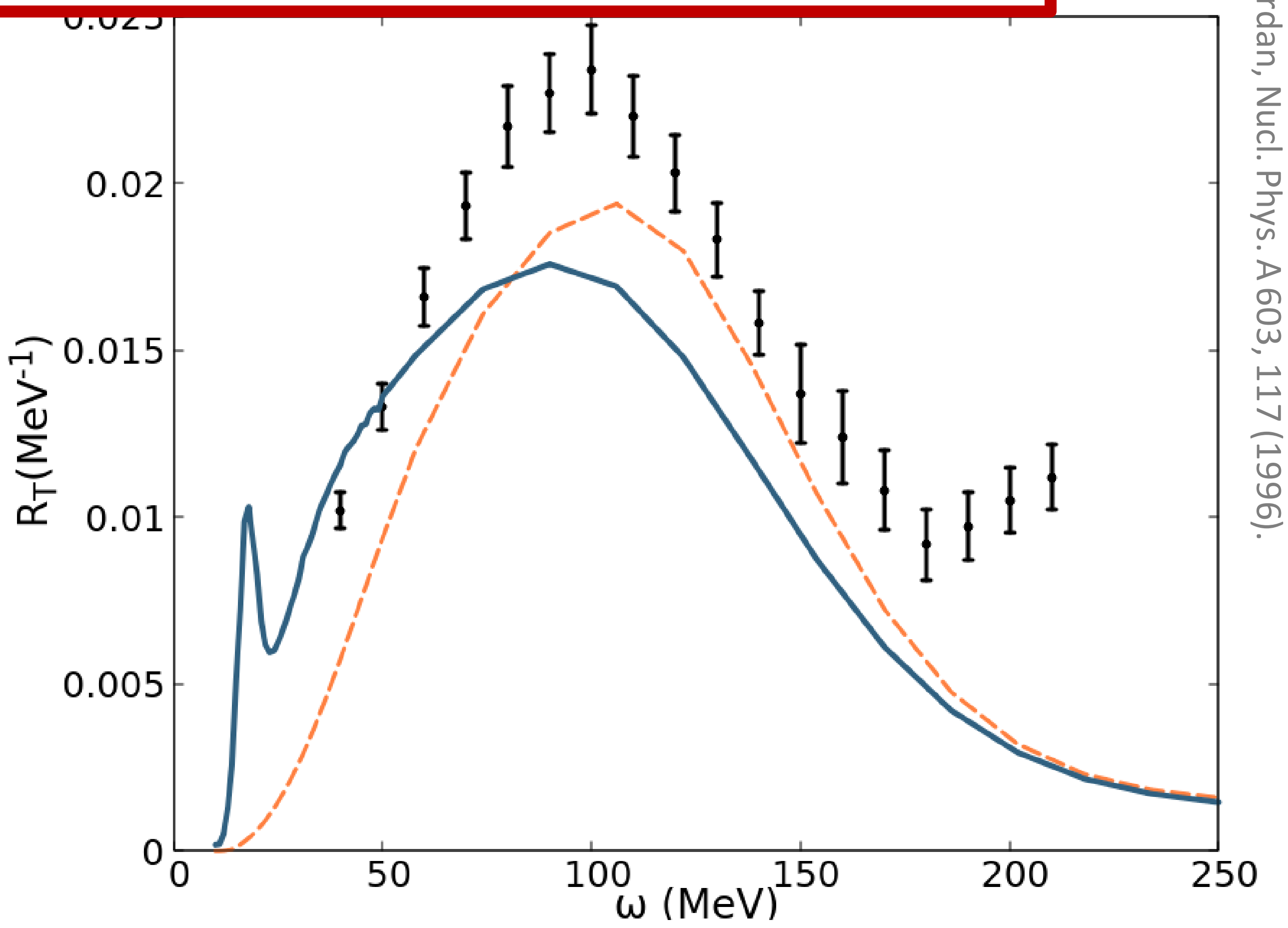
- **Knocked out nucleon**: distorted wave function computed as a solution of the Dirac equation in the continuous with the energy dependent relativistic mean-field (ED-RMF) potential.



Knocked out nucleon

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

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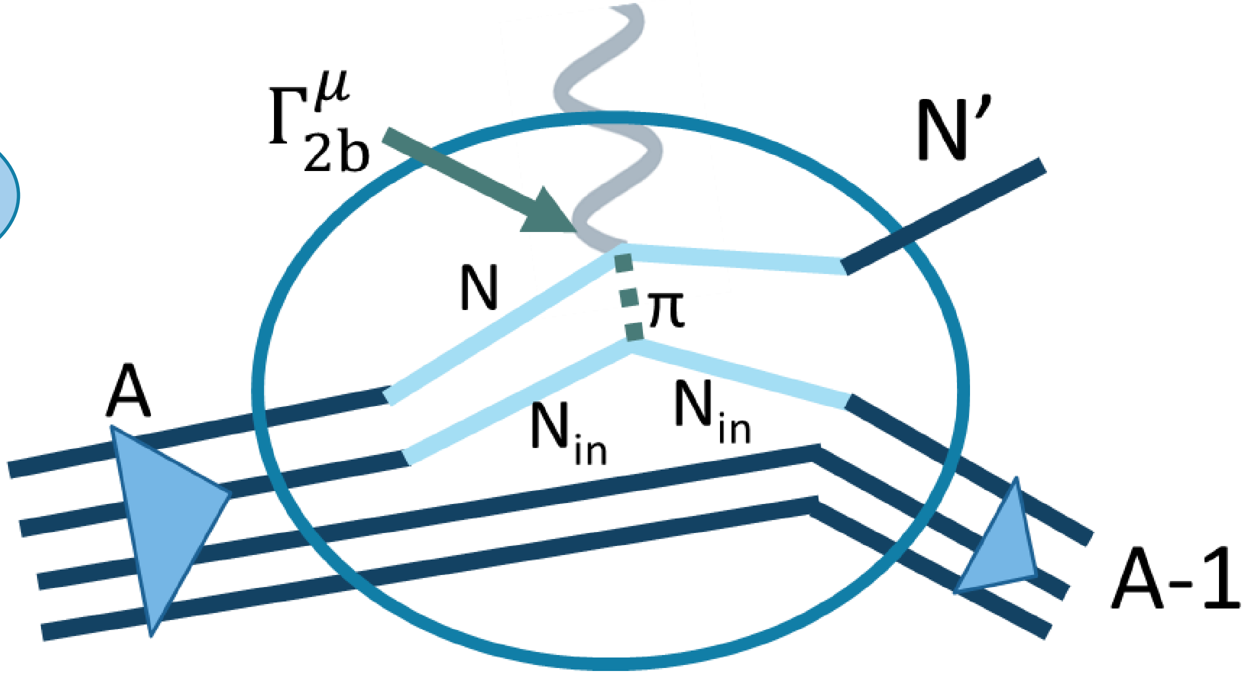
- Theoretical framework
  - Independent Particle Shell Model
  - Hadronic current: RMF and FSI
  - **Two-body meson-exchange currents in particle-hole excitations**

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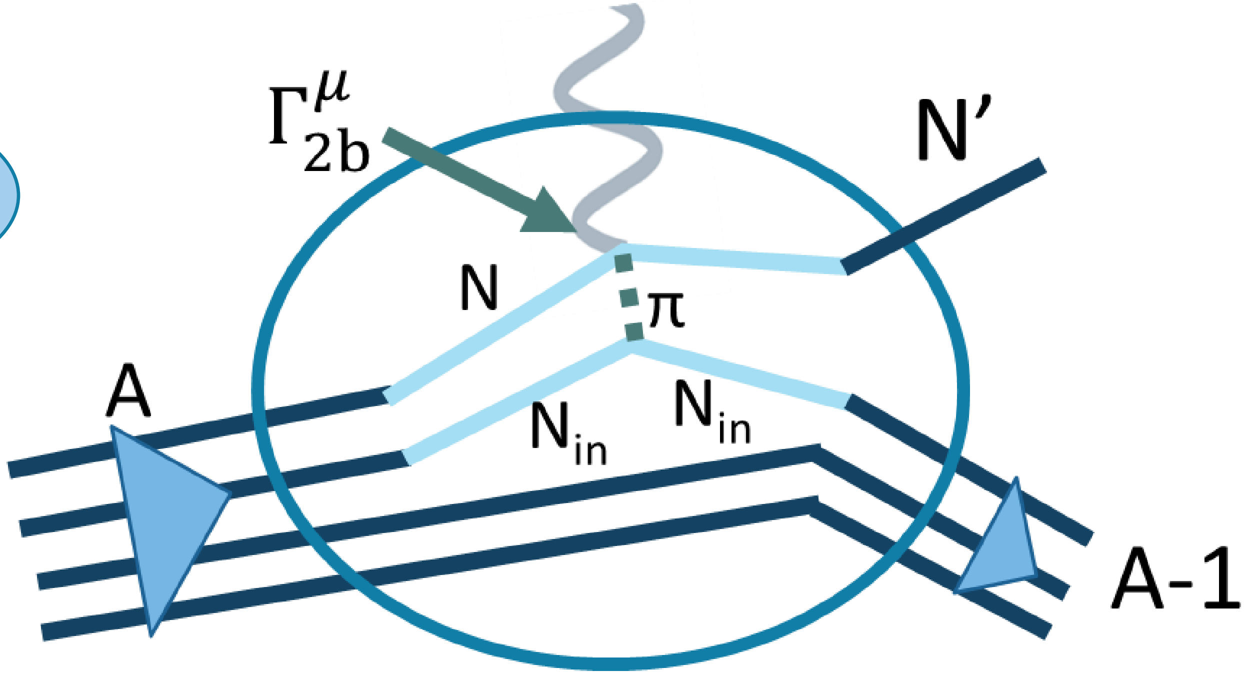
- We include **one-pion exchange effects** by incorporating **two-body meson-exchange currents** with a final paticle-hole state.

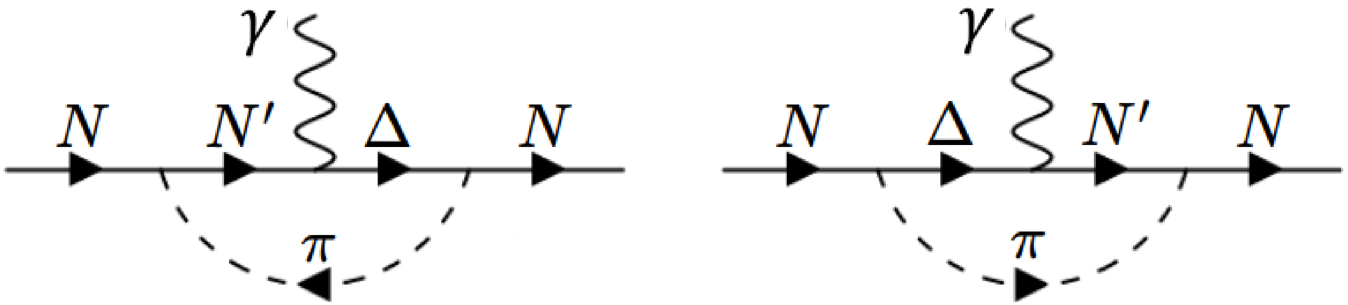
$$J^{\mu}_{had} = J^{\mu}_{had,1b} + J^{\mu}_{had,2b}$$

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

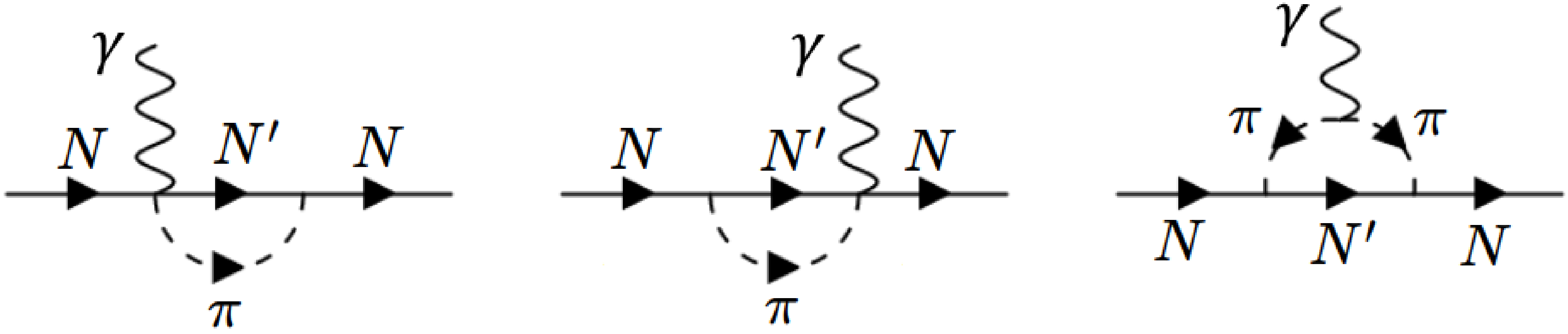


Meson exchange currents

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

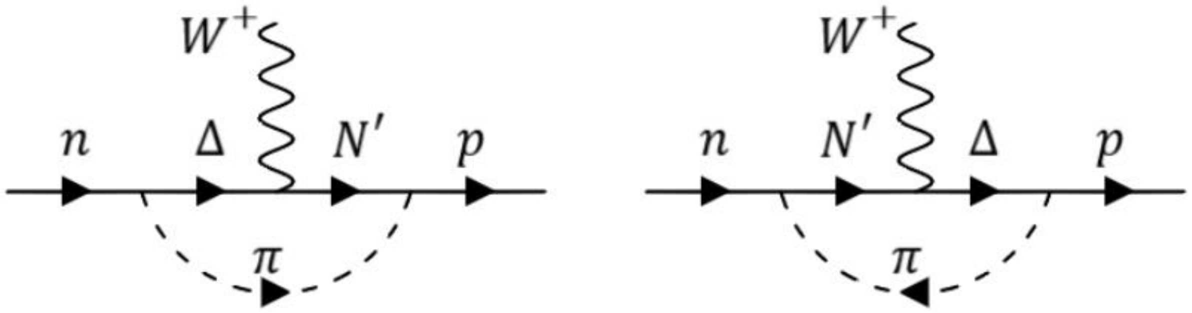


  - ChPT background



Meson exchange currents

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



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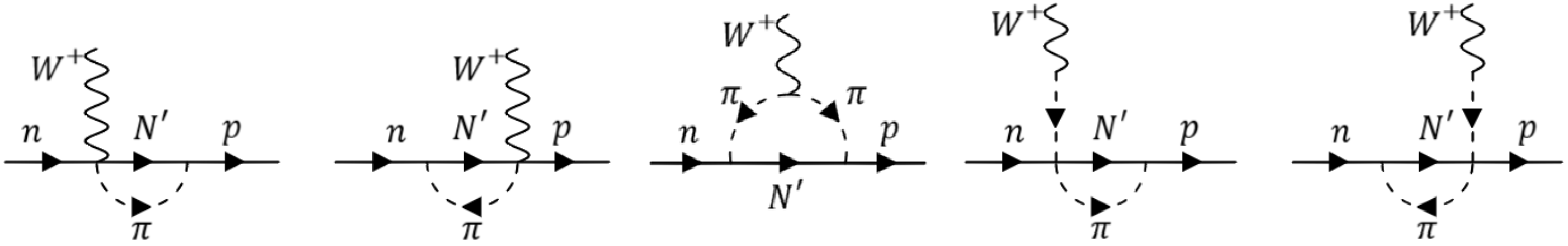

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- Theoretical framework
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- **Electron-nucleus scattering**

Outline

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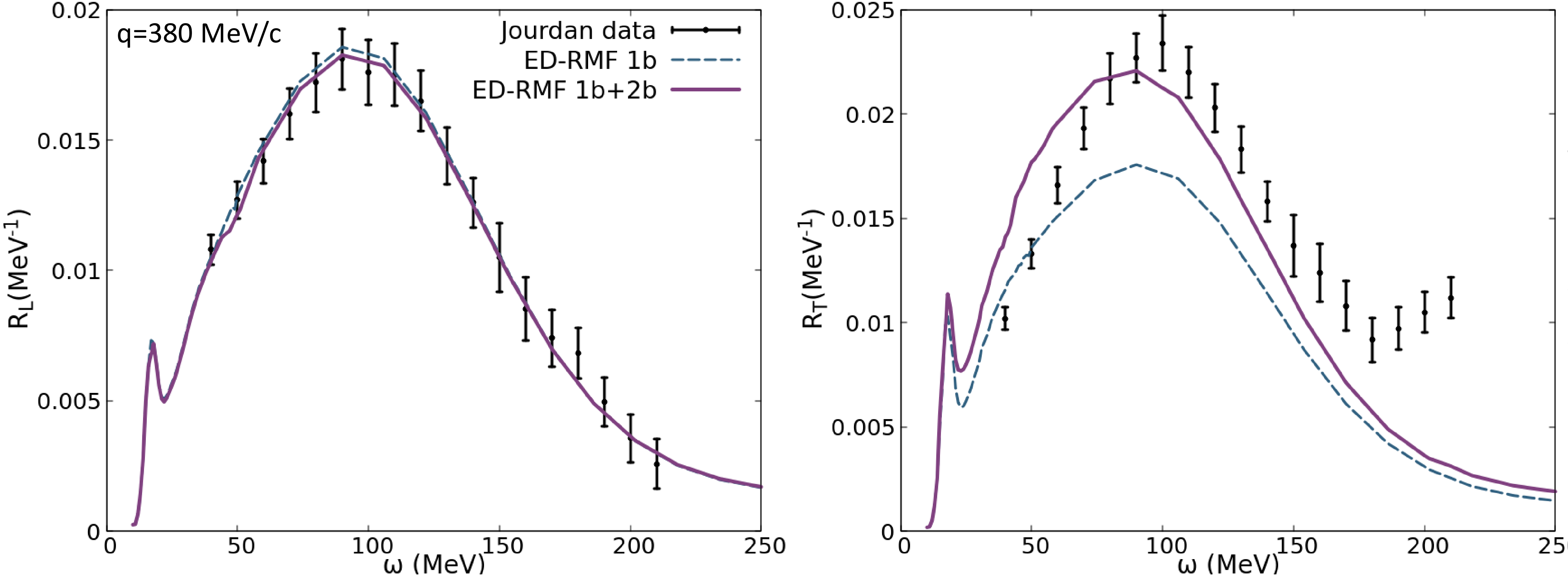
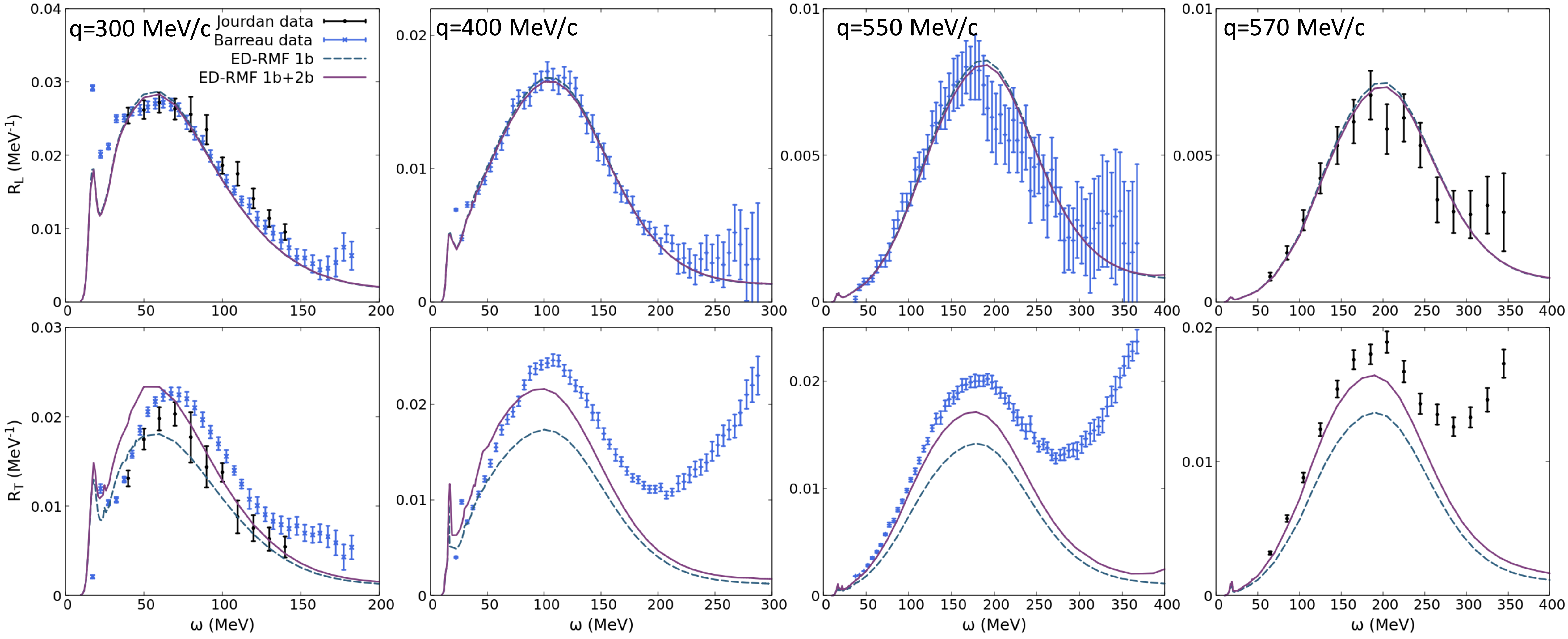
    - **^{12}C inclusive responses**

^{12}C electromagnetic inclusive responses



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

^{12}C electromagnetic inclusive responses



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

Outline

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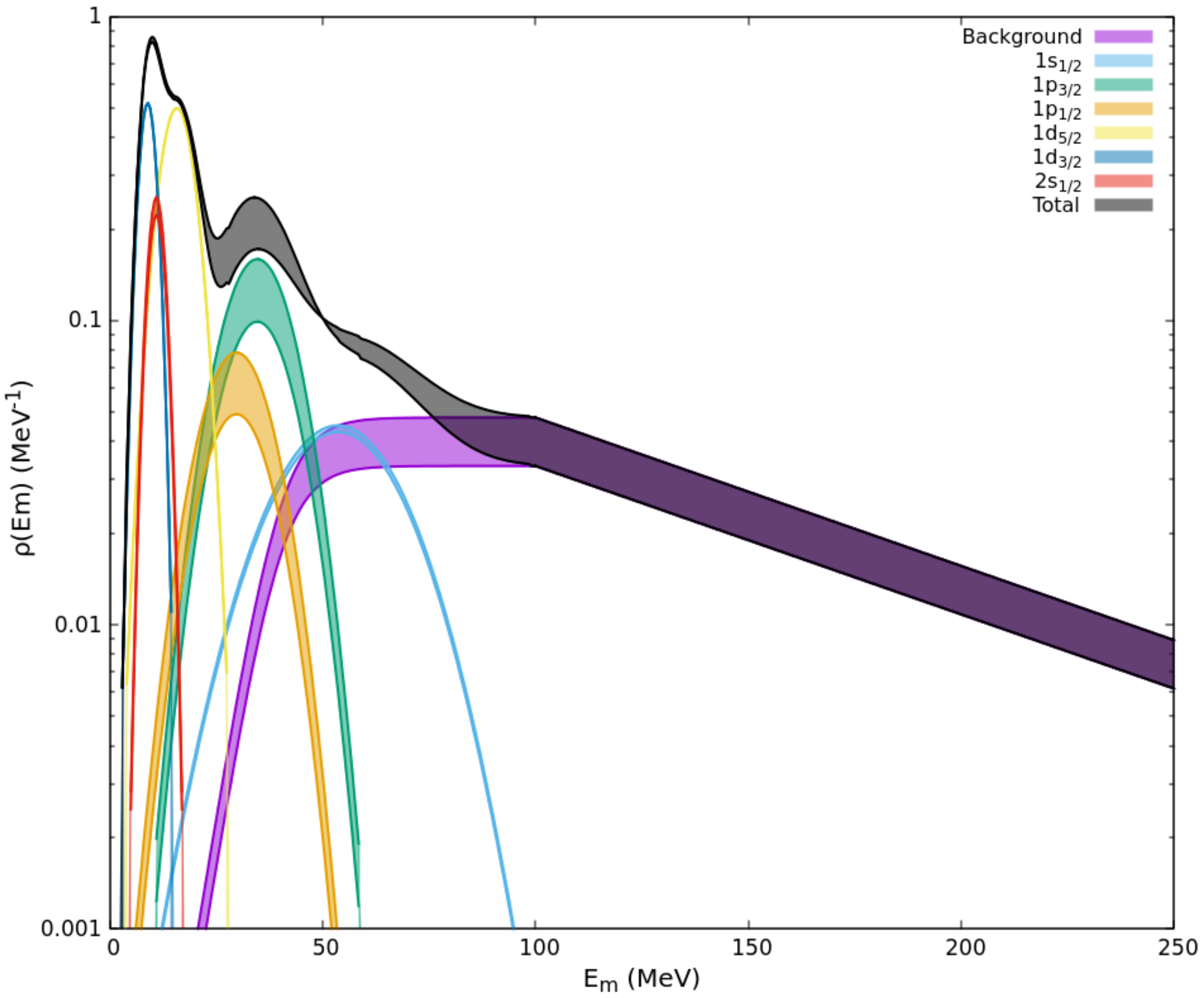
- Electron-nucleus scattering
  - ^{12}C inclusive responses
  - **^{40}Ca inclusive responses and cross section**

^{40}Ca independent particle shell model

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

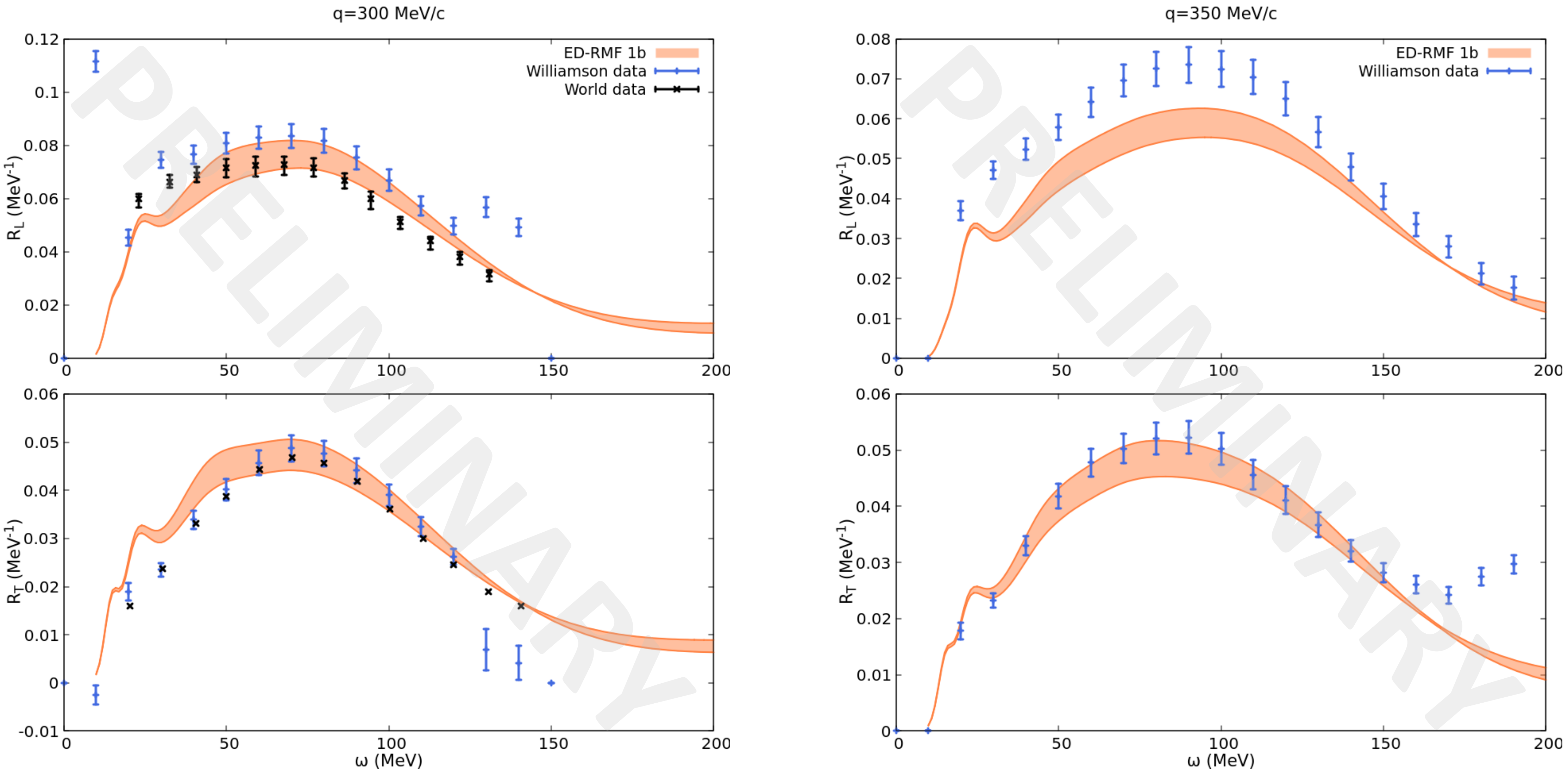
Shell model state	Occupation probability	
	Ca(e,e'p)	Ca(p,2p)
$1d_{3/2}$	0.65 ± 0.07	0.65 ± 0.05
$2s_{1/2}$	0.64 ± 0.06	0.53 ± 0.04
$1d_{5/2}$	0.83 ± 0.05	0.85 ± 0.09
$1p_{3/2}+1p_{1/2}$	-	0.49 ± 0.07
$1s_{1/2}$	-	0.89 ± 0.09

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

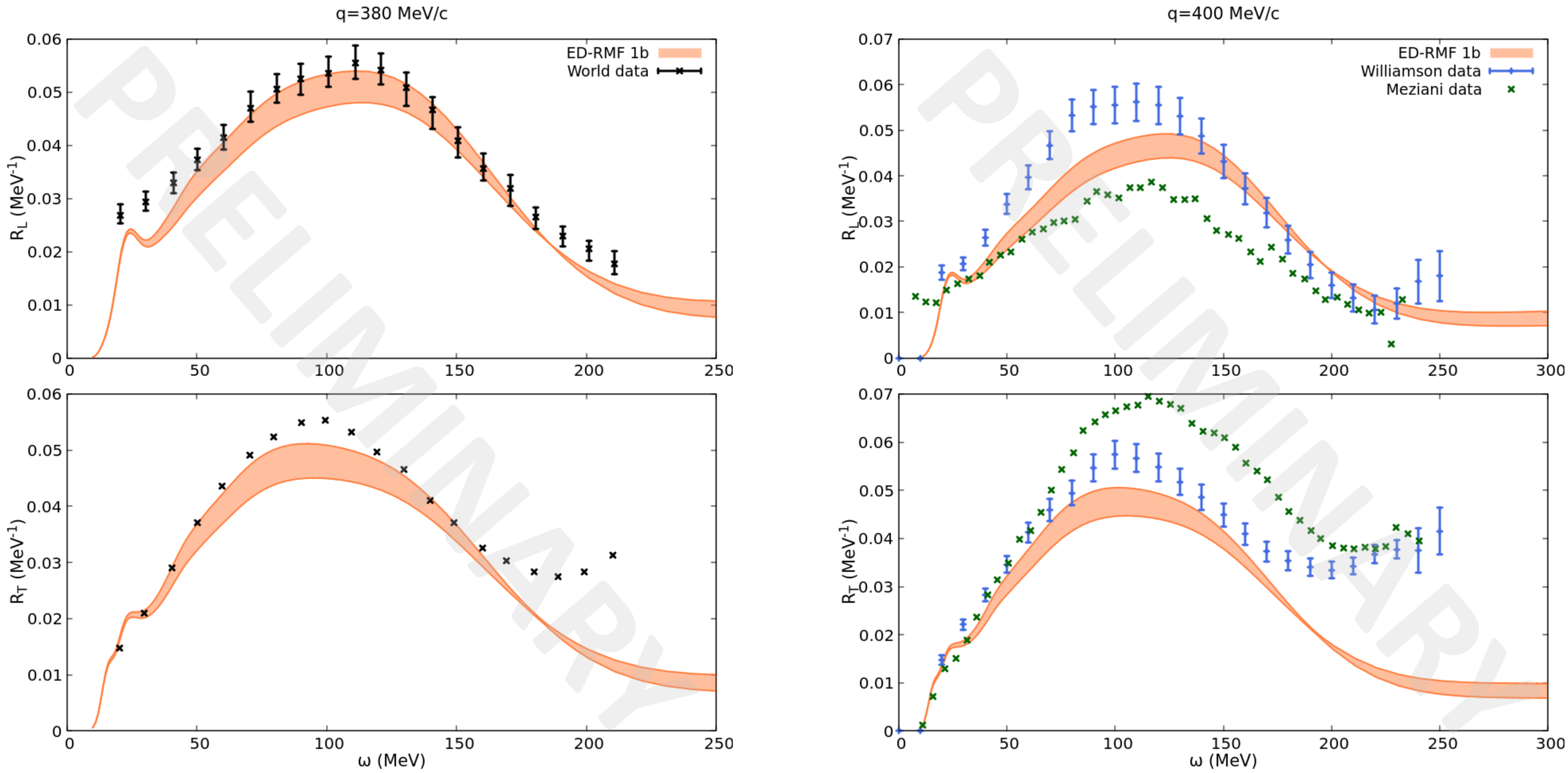


40Ca(e.e'p) occupations: G.J. Kramer et al., Phys. Lett. B 227, 199 (1989)
40Ca(p,2p) occupations: Y. Yasuda, Ph.D. thesis, Kyoto University (2012)

^{40}Ca electromagnetic inclusive responses



^{40}Ca electromagnetic inclusive responses



^{40}Ca electromagnetic inclusive cross section

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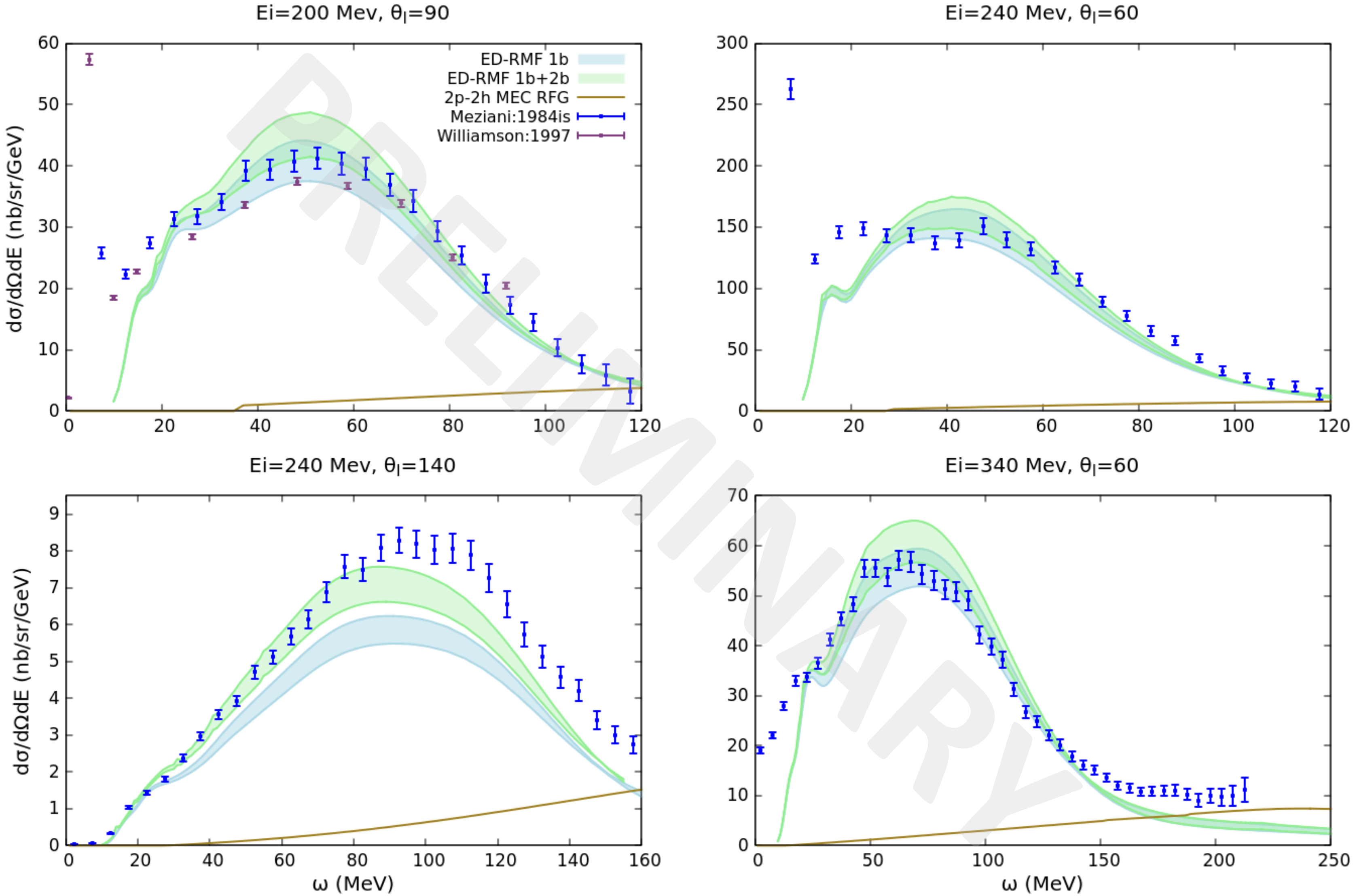
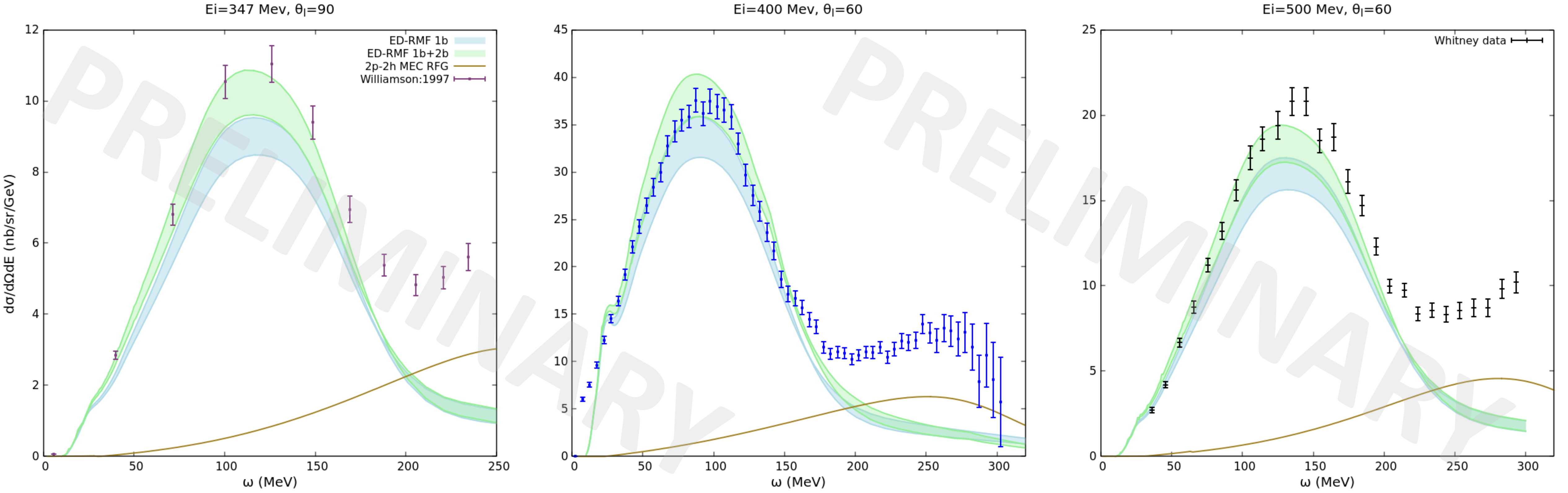


Data: discovery.phys.virginia.edu/research/groups/qes-archive/data/40Ca.html

^{40}Ca electromagnetic inclusive cross section



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

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  - Two-body meson-exchange currents in particle-hole excitations
- Electron-nucleus scattering
  - ^{12}C inclusive responses
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- **Neutrino-nucleus scattering**

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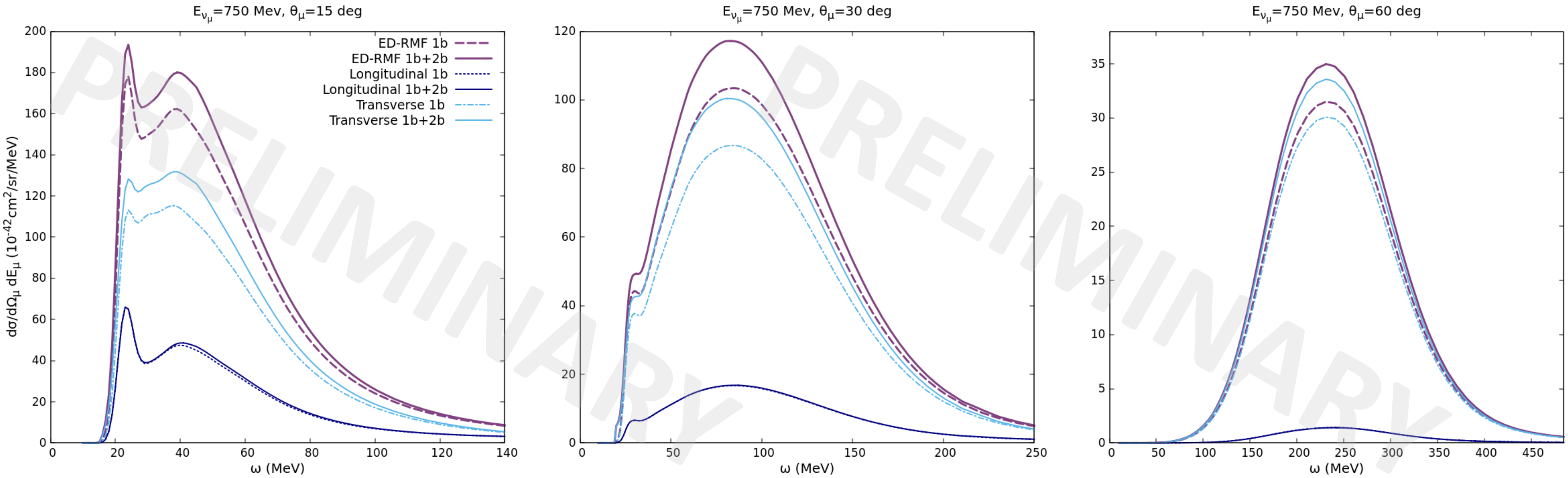
- Neutrino-nucleus scattering
  - **^{12}C inclusive cross section**

^{12}C-ν_μ inclusive cross section



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- **Conclusions and future prospects**

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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- We have developed **a relativistic mean-field based model**, with **one- and two-body current** contributions to the **1p-1h** excitation.
  - The use of a **realistic treatment of the nuclear structure** is fundamental to describe the experimental data.

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

- **Electron**-nucleus results:

Conclusions and future prospects

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  - **^{40}Ca results** needs a better control of shell model occupations. Still a puzzle for us..., it requieres further studies. (See also Joanna Sobczyk talk).

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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

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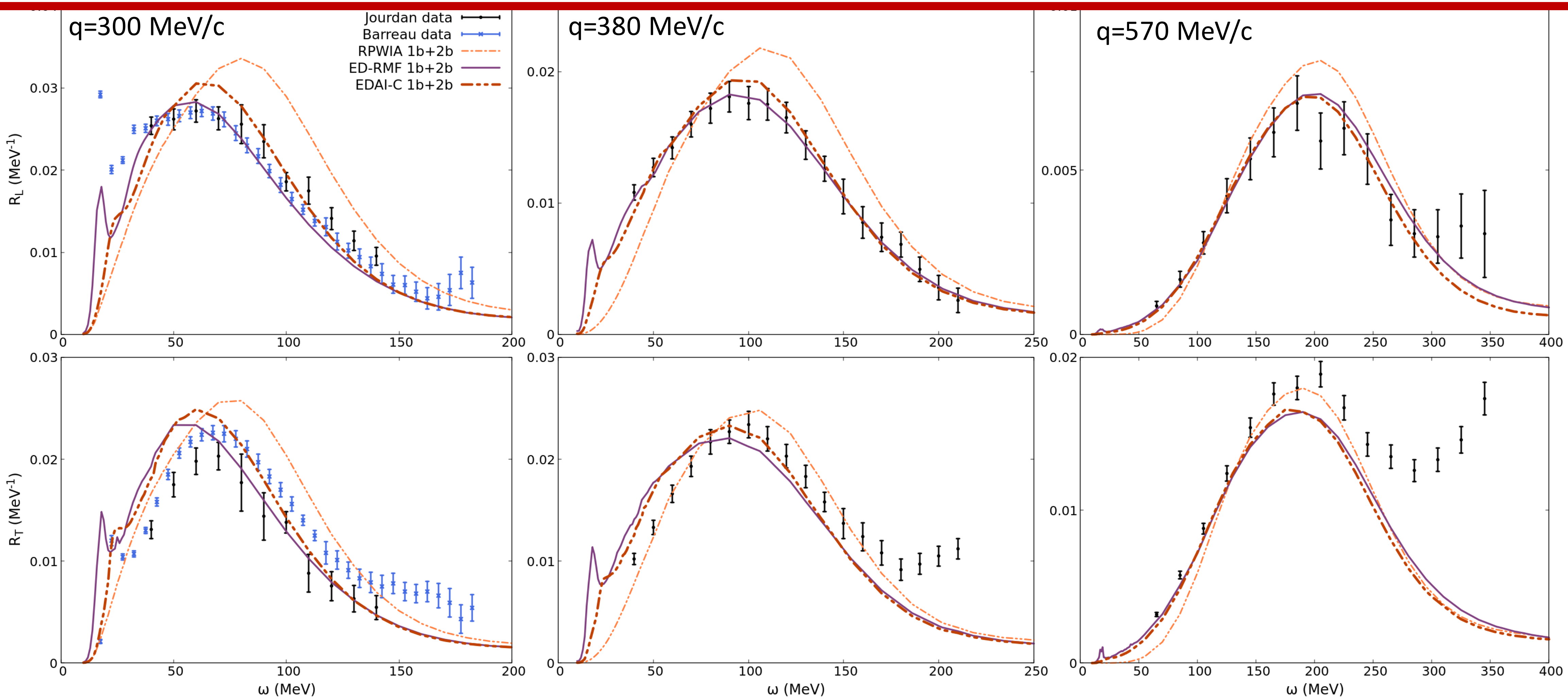
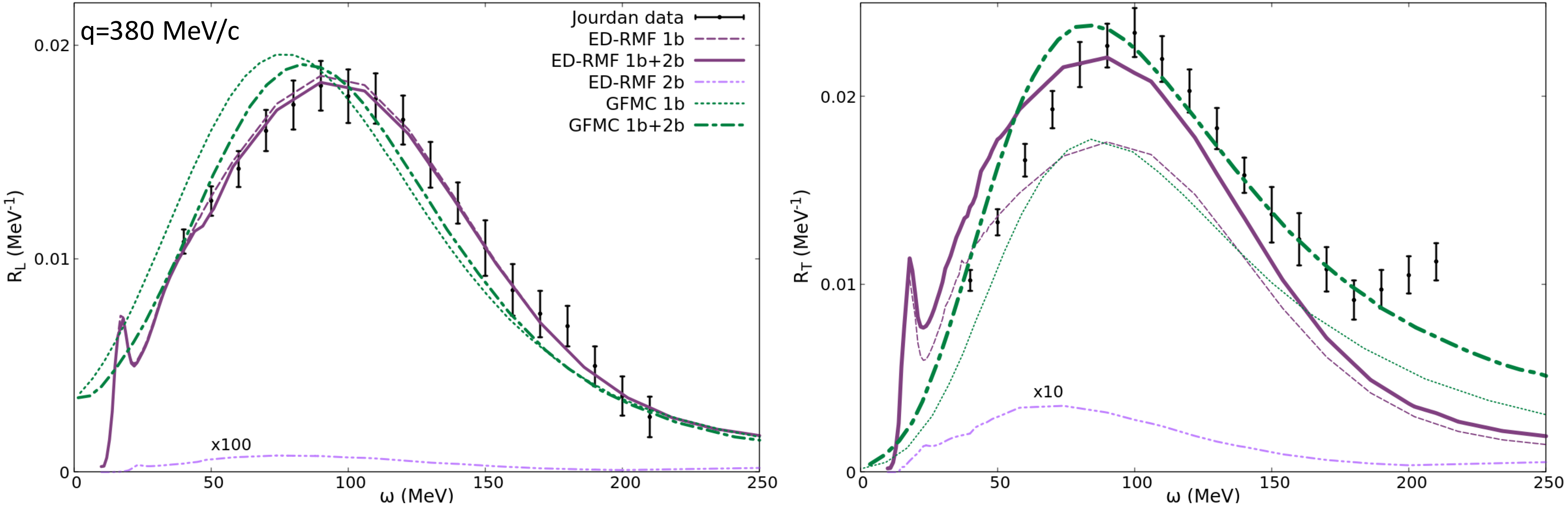
Spurious contributions appear from **non-orthogonality** between initial and final states



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

Comparison to previous computations

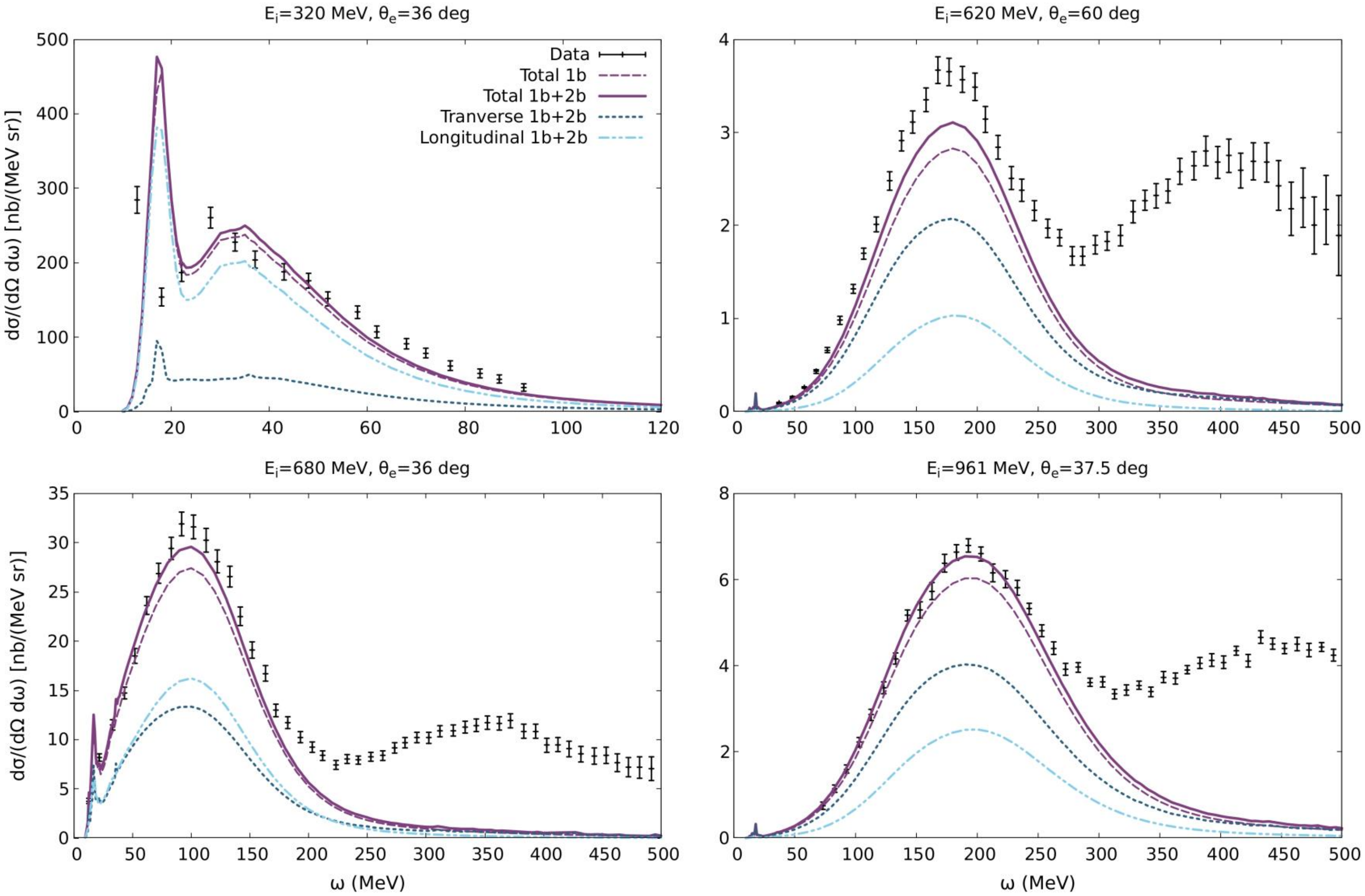
- Two completely different theoretical approaches
  - **Ab initio non-relativistic Green's function Monte Carlo** (GFMC).
  - **ED-RMF**: fully **relativistic model** and coherent **quantum mechanical** description of the nucleonic states, incorporating **realistic dynamics and final state interactions**



- 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



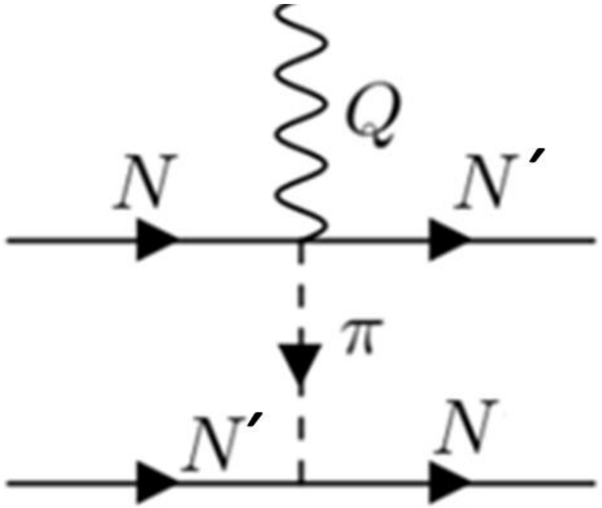
Data: P. Barreau et al., Nuclear Physics A 402 (3) (1983)
R. M. Sealock et al., Phys. Rev. Lett. 62 (1989)

Intermediate bound-nucleon state

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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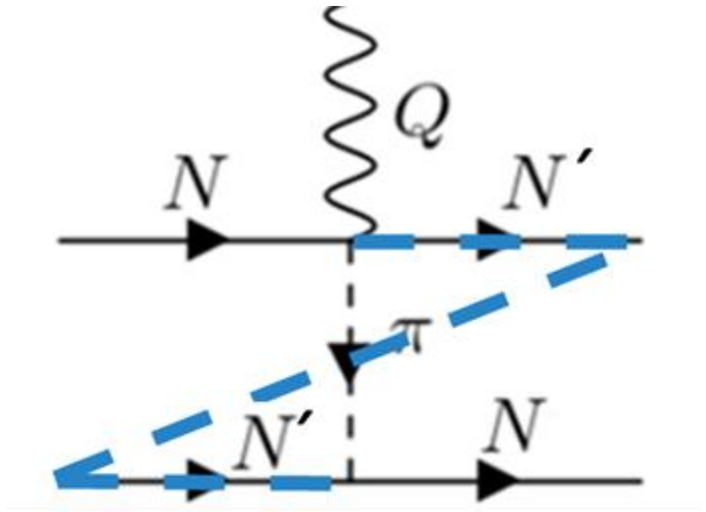

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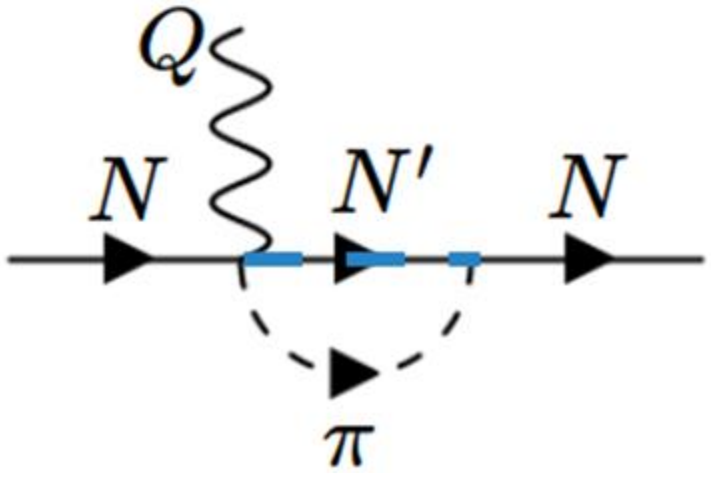

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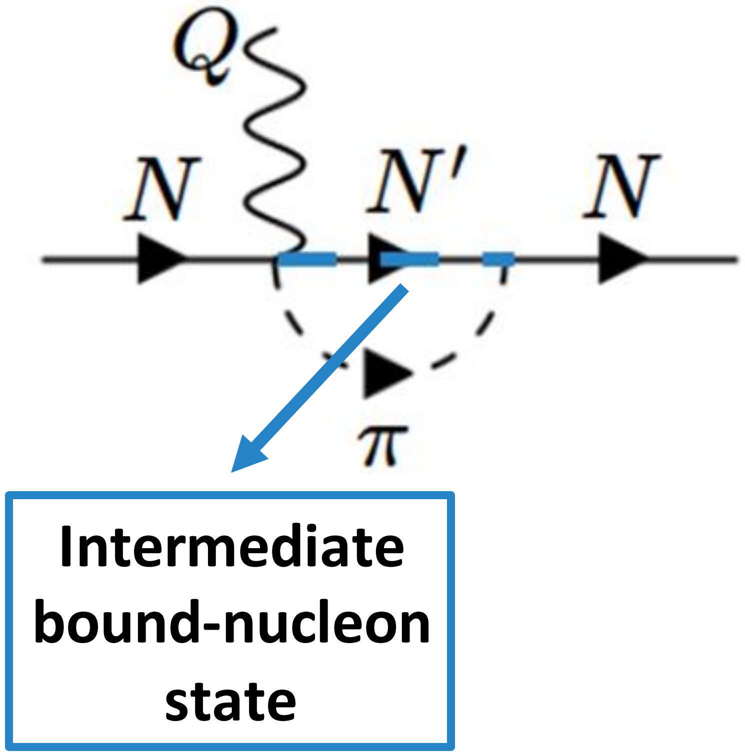

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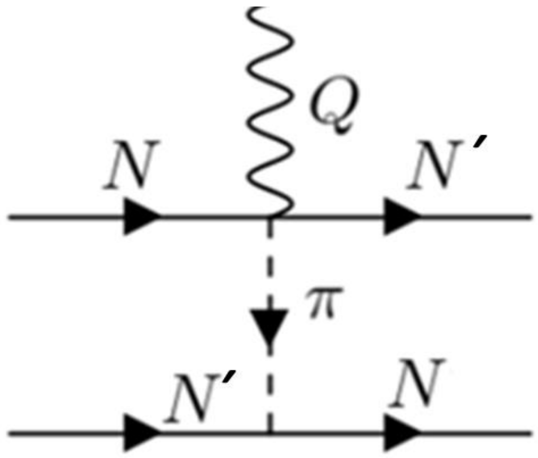

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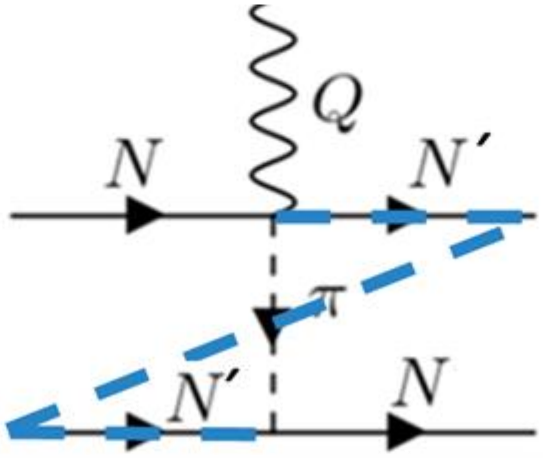

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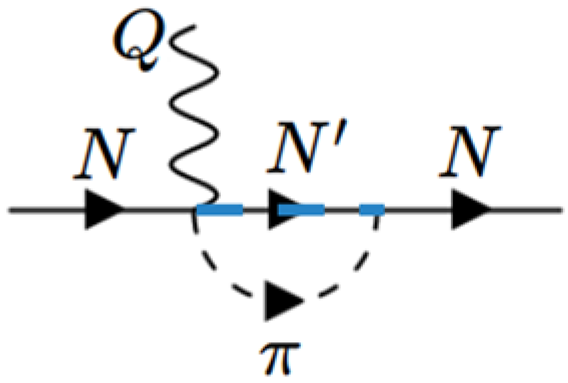

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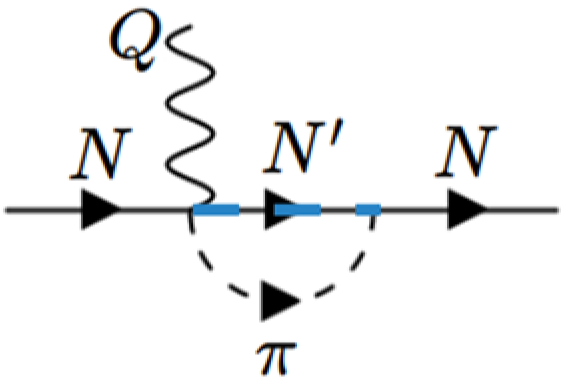
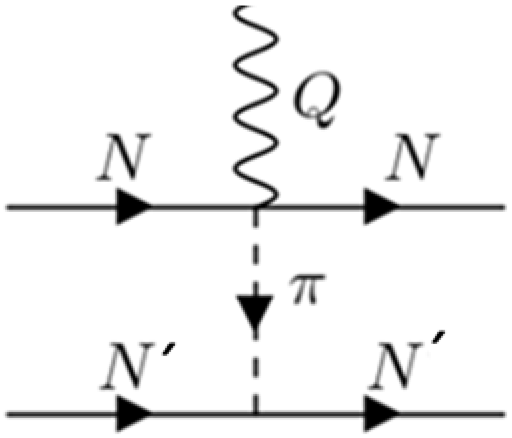


Direct terms



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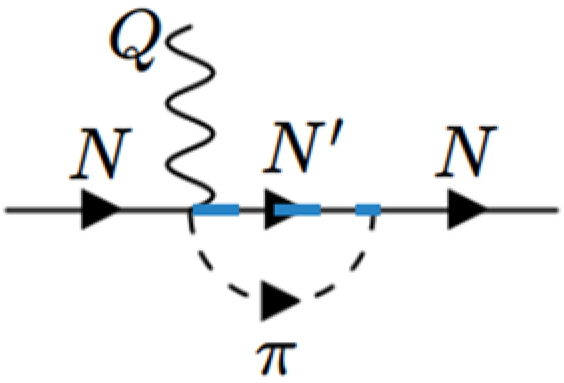

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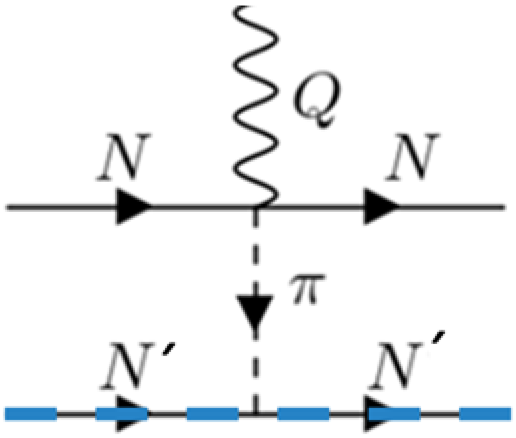

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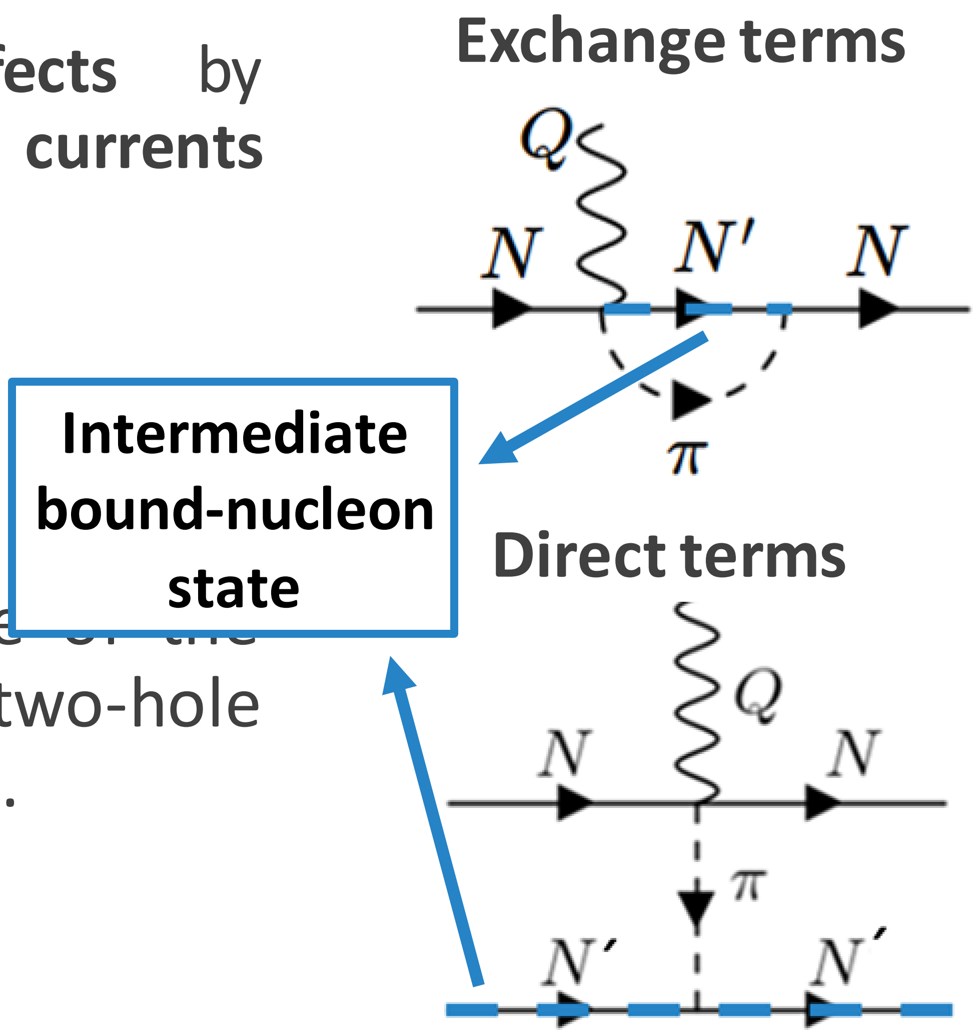
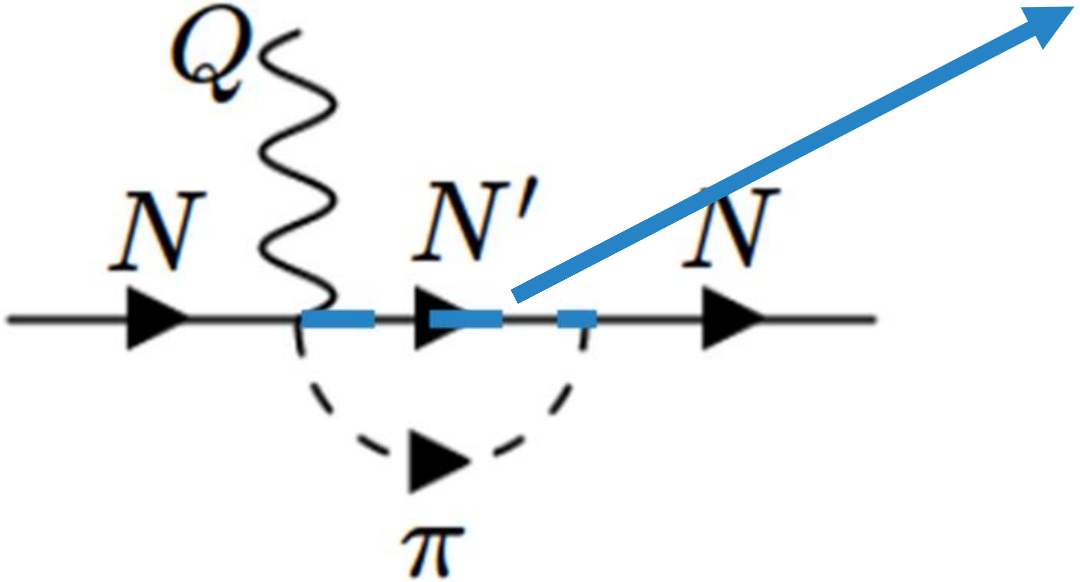


Intermediate bound-nucleon state

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



More realistic case:
Intermediate RMF-nucleon approach

Simplified case:
Intermediate RFG-nucleon approximation

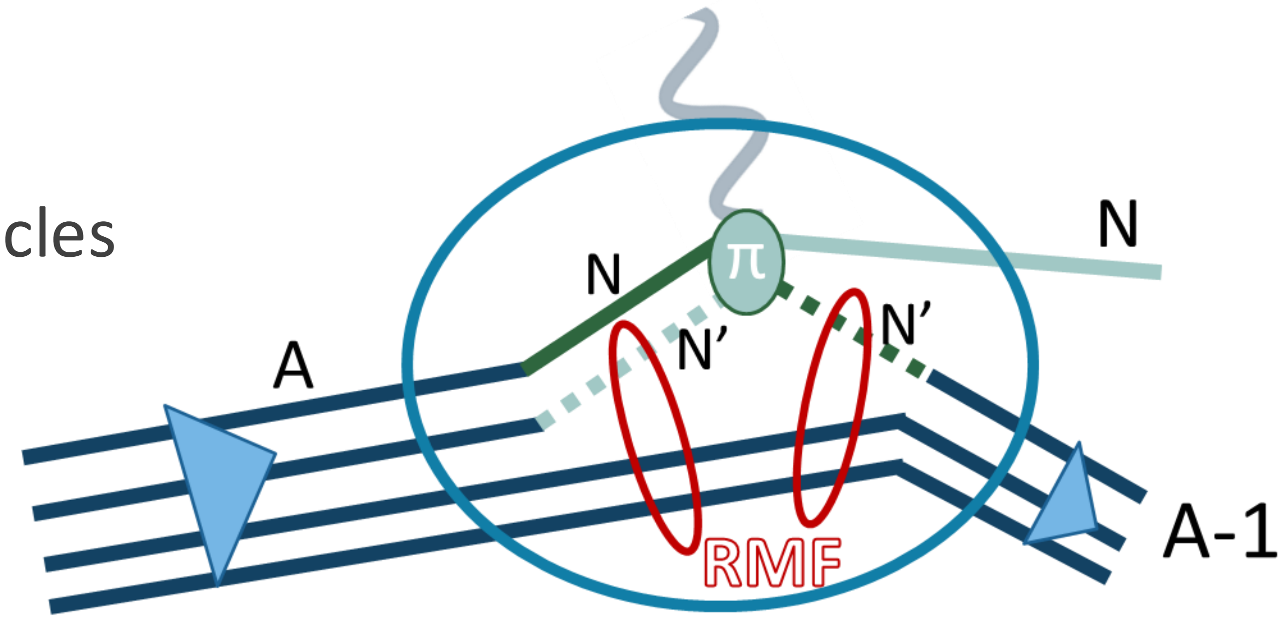
Approximated nuclear effects case:
Intermediate RFG*-nucleon approximation

Intermediate bound-nucleon state

More realisitic case:

Intermediate RMF-nucleon approach

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



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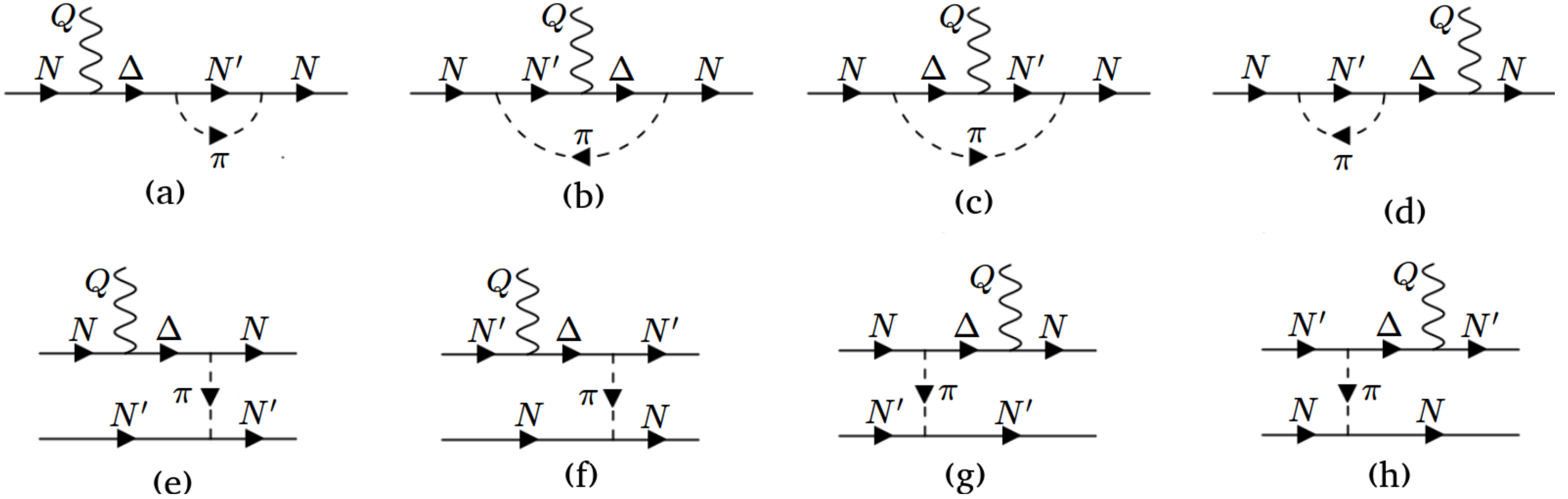
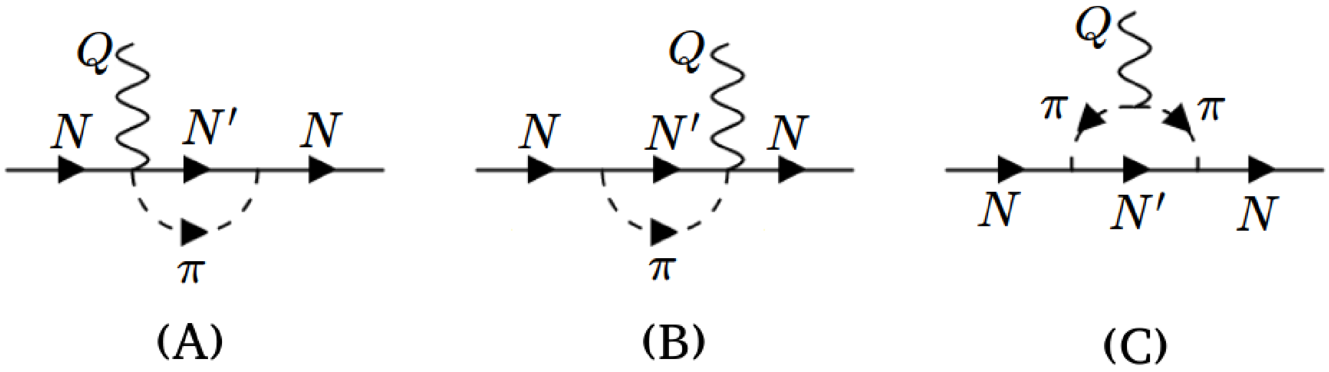
Intermediate RMF-nucleon approach

- **MEC contributions**
  - Delta resonance mechanism



  - ChPT background



Intermediate RMF-nucleon approach

- Two-body current

$$J^{\mu}_{2b} = \int d\boldsymbol{p} \int \frac{d\boldsymbol{p_p}}{(2\pi)^{3/2}} \int \frac{d\boldsymbol{p_h}}{(2\pi)^{3/2}} \, \bar{\Psi}^{s}\left(\boldsymbol{p}+\boldsymbol{p_h}+\boldsymbol{q}-\boldsymbol{p_p}, \boldsymbol{p_N}\right) \Gamma^{\mu}_{2b} \, \Psi^{m_j}_{\kappa}(\boldsymbol{p})$$

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

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Intermediate RMF-nucleon approach

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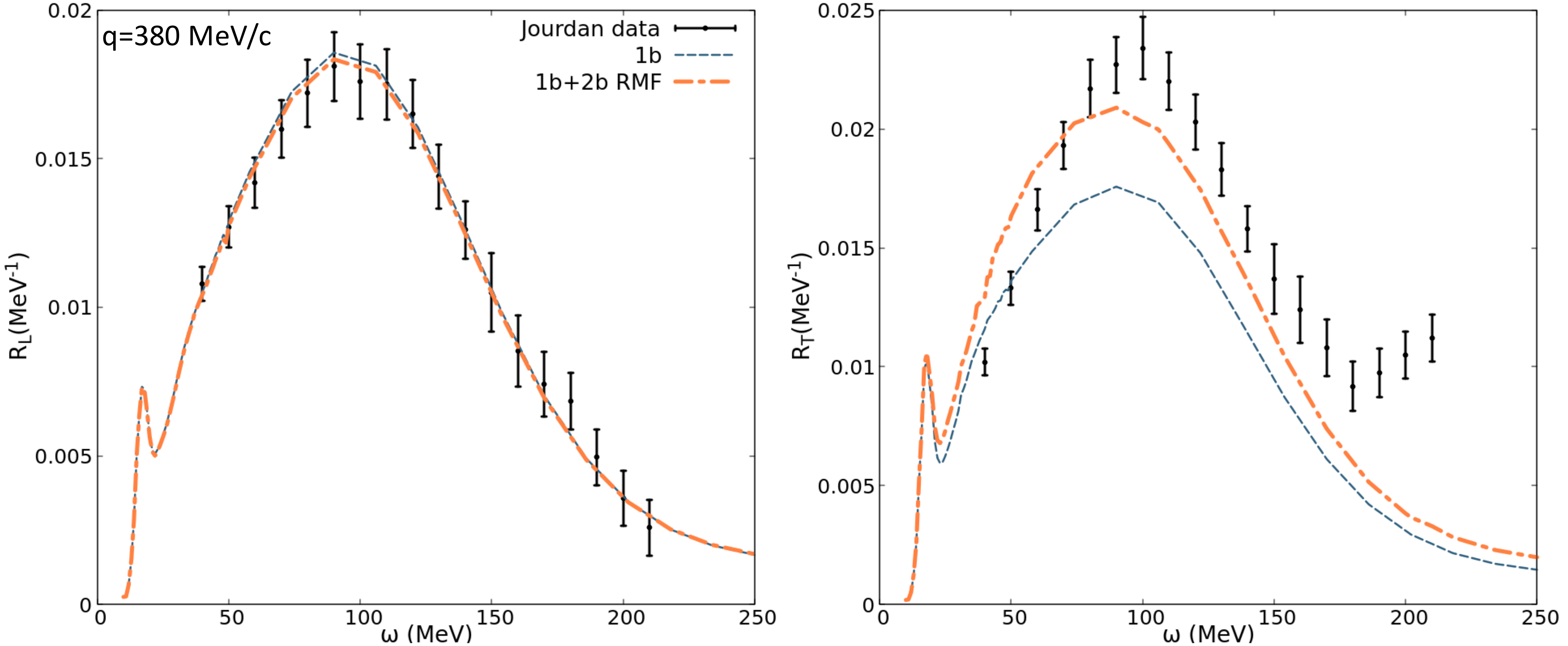
^{12}C electromagnetic inclusive responses



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

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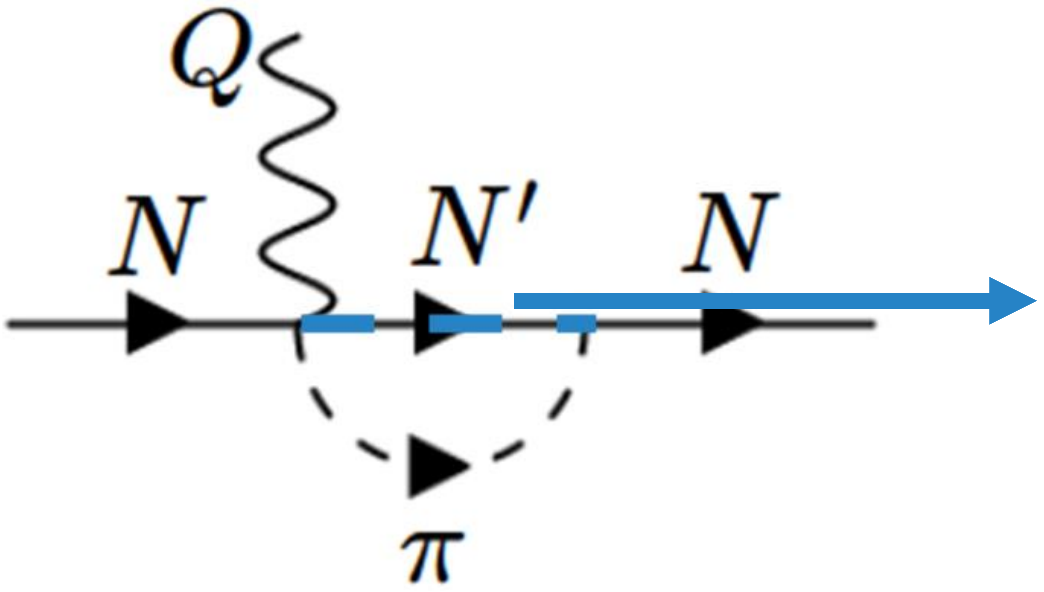

More realistic case:
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Simplified case:
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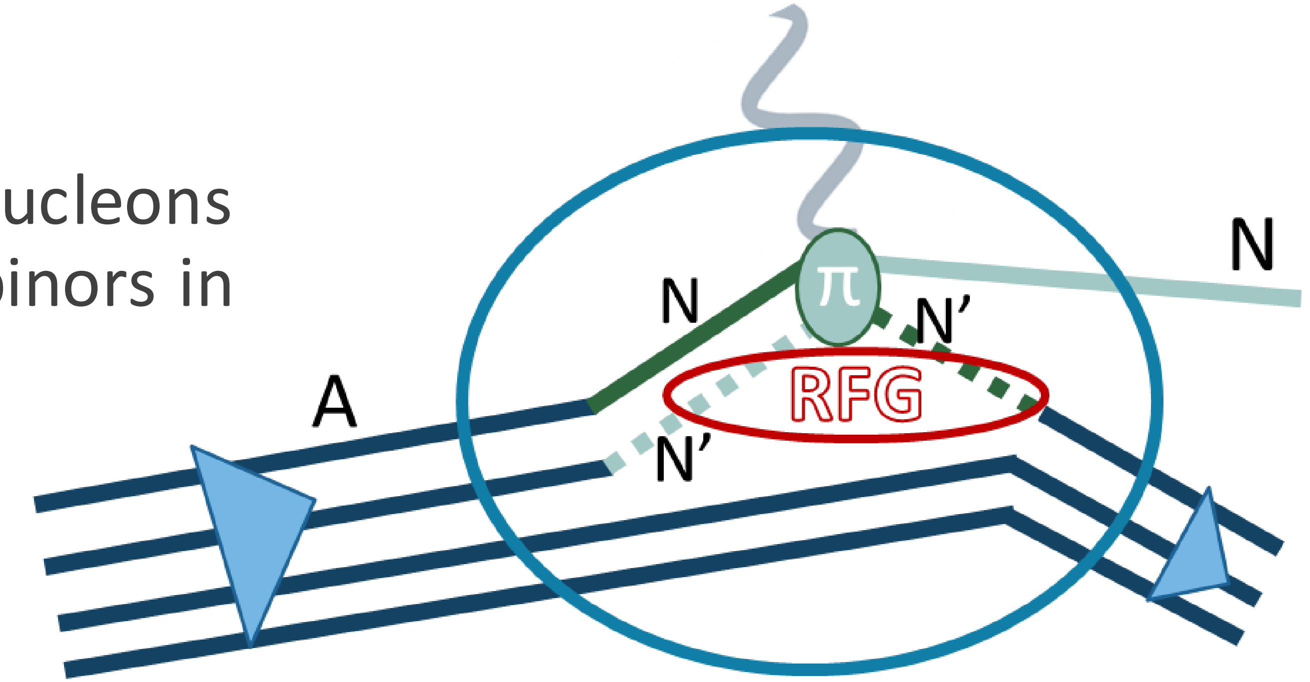
Intermediate bound-nucleon state

Simplified case:

Intermediate RFG-nucleon approximation

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



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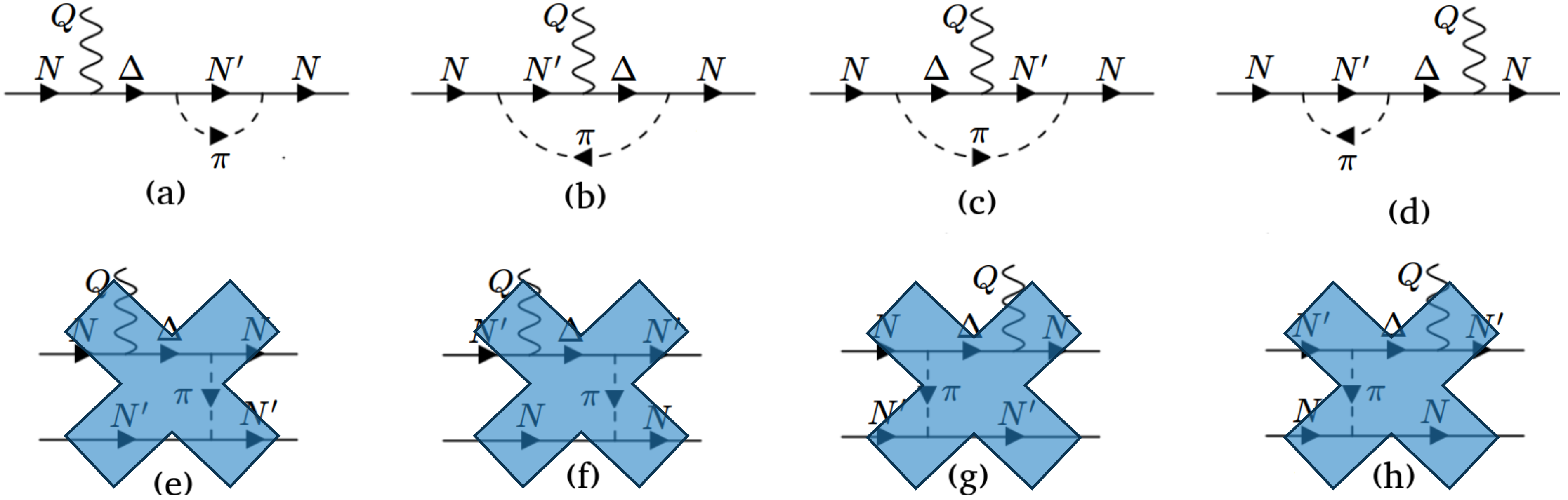
Intermediate RFG-nucleon approximation

- **MEC contributions**
  - Delta resonance mechanism



  - ChPT background

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

Intermediate RFG-nucleon approximation

- **MEC contributions**
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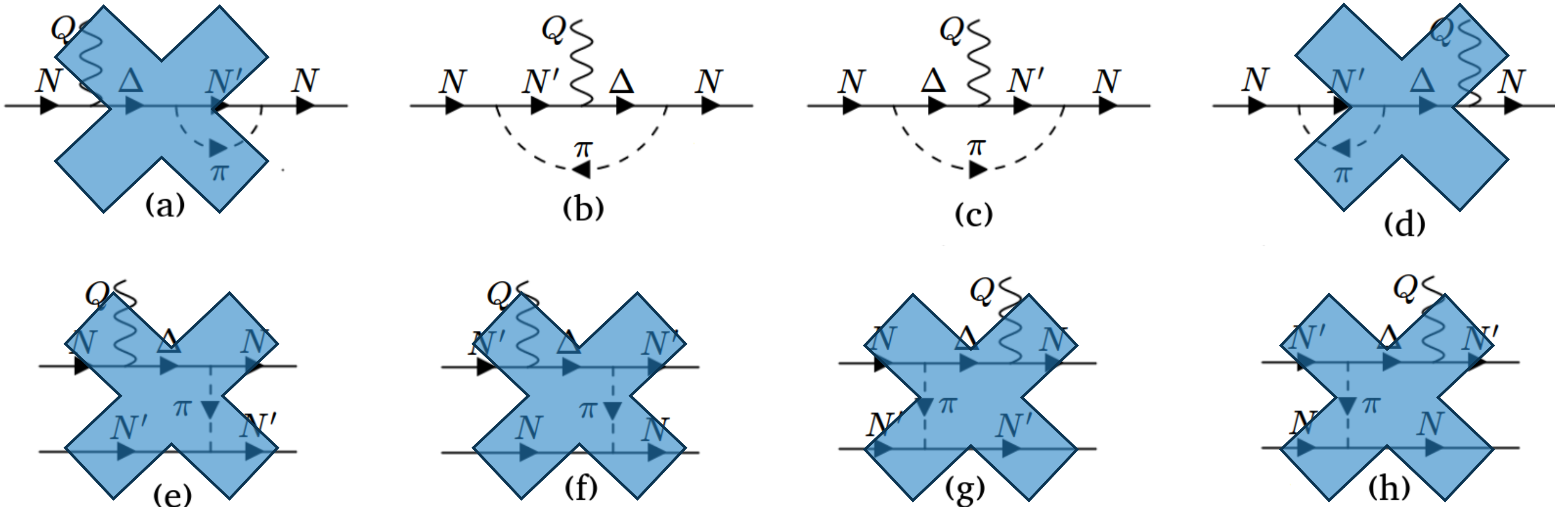

  - ChPT background

(A) (B) (C)

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

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Intermediate RFG-nucleon approximation

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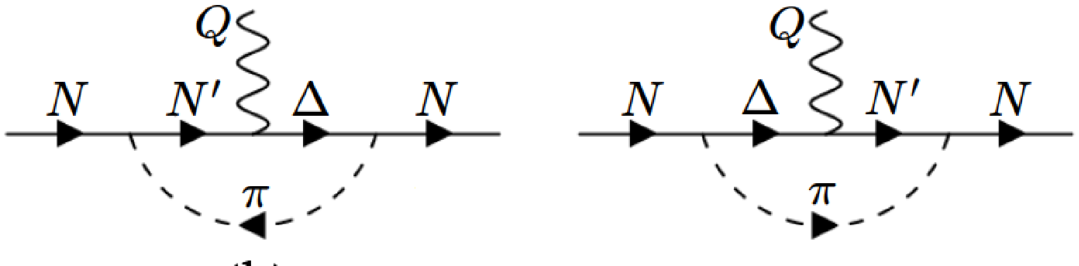

(b) (c)

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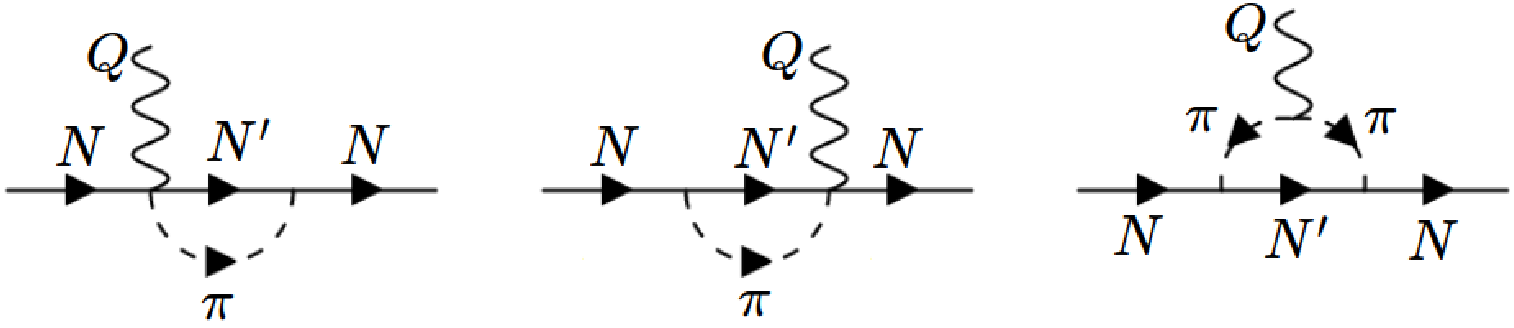

(A) (B) (C)

Intermediate RFG-nucleon approximation

- Two-body current

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

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

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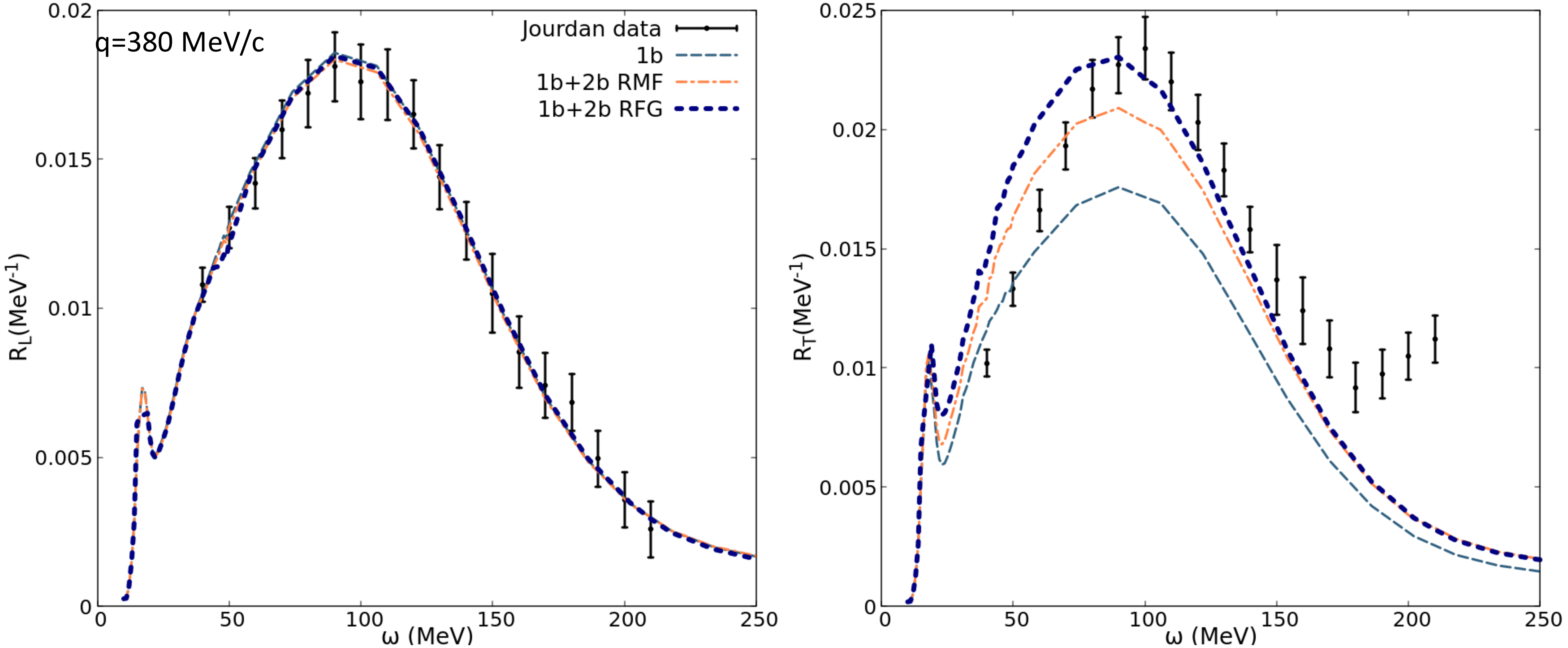
Intermediate RFG-nucleon approximation

^{12}C electromagnetic inclusive responses



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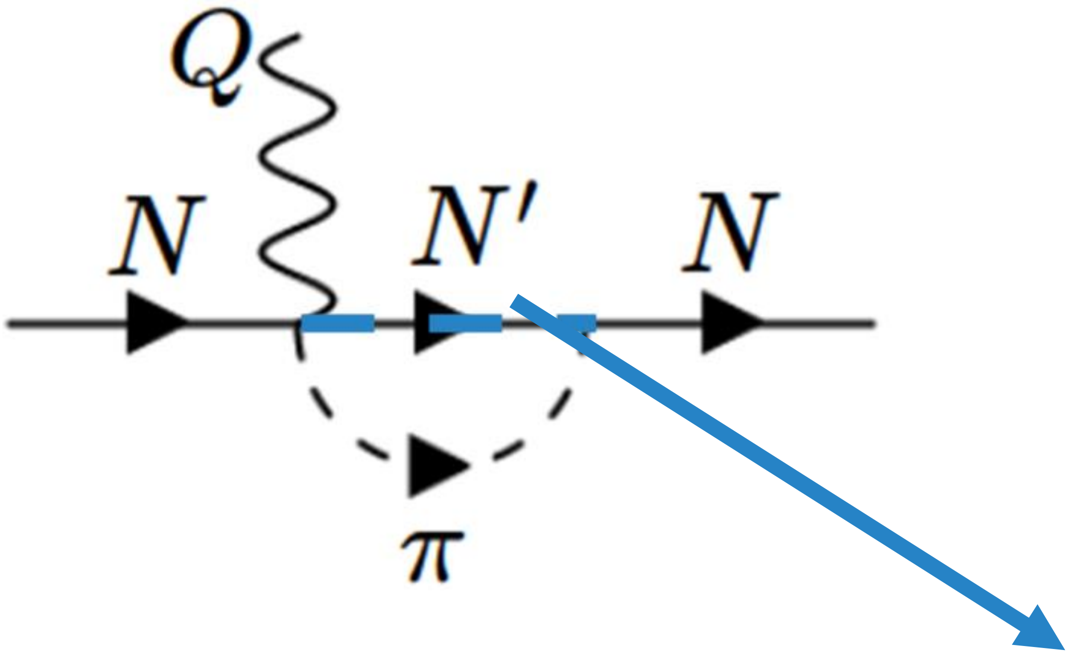

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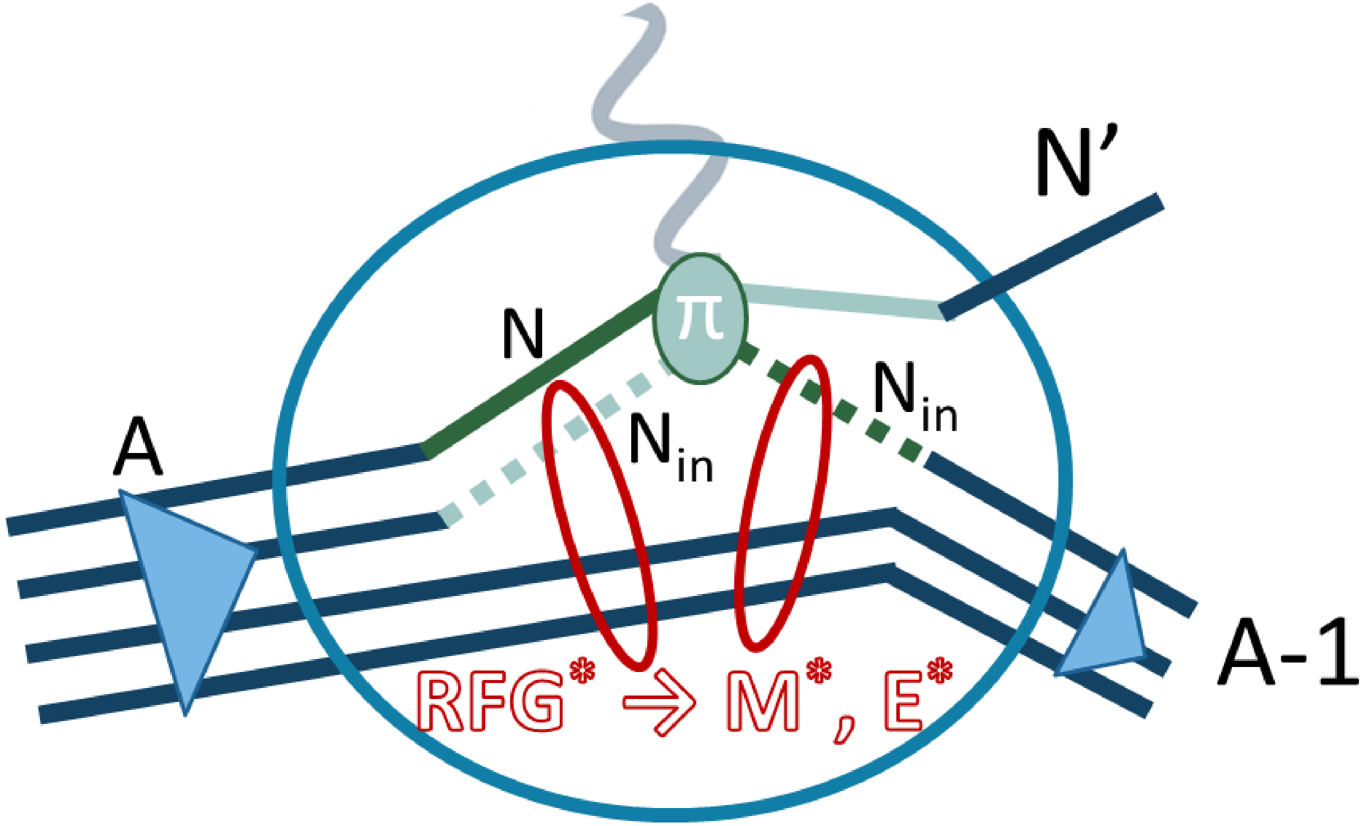
Intermediate bound-nucleon state

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.

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

- α=0.8 and E_v=141 MeV for ^{12}C.



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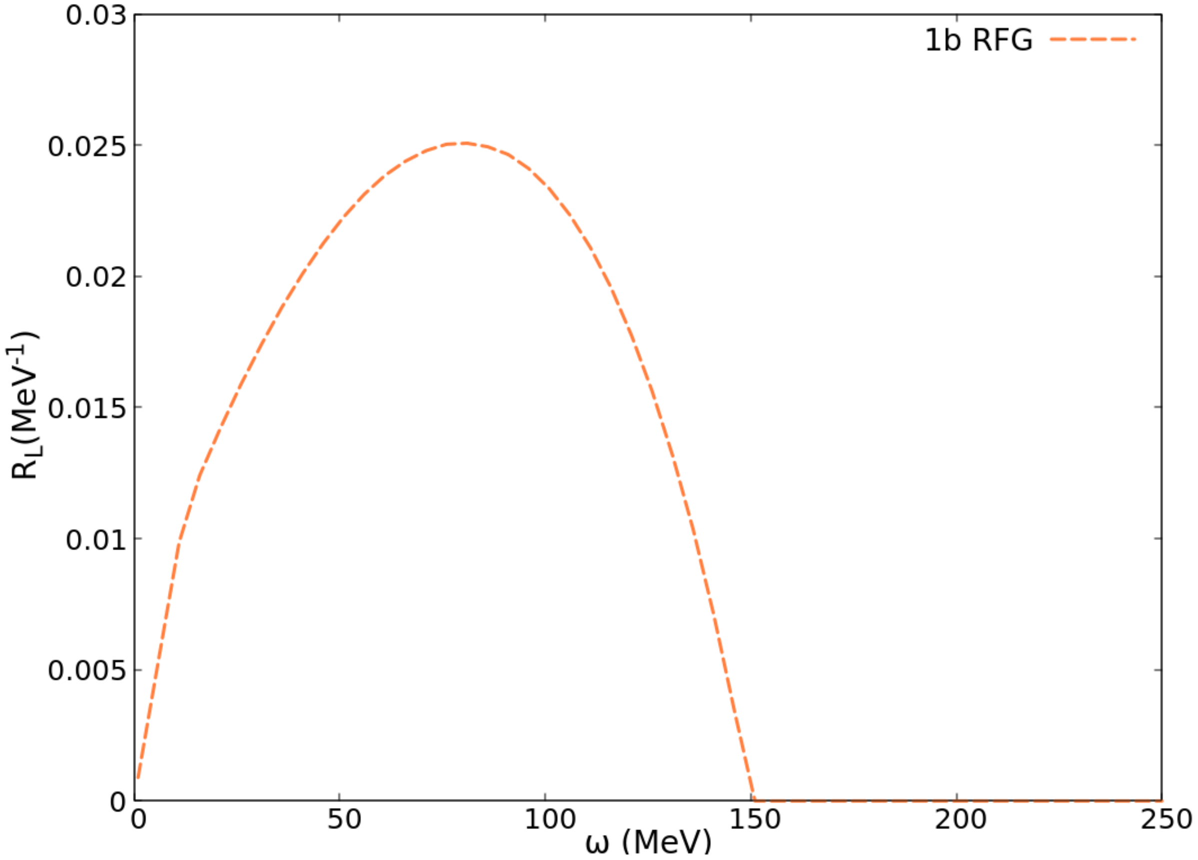
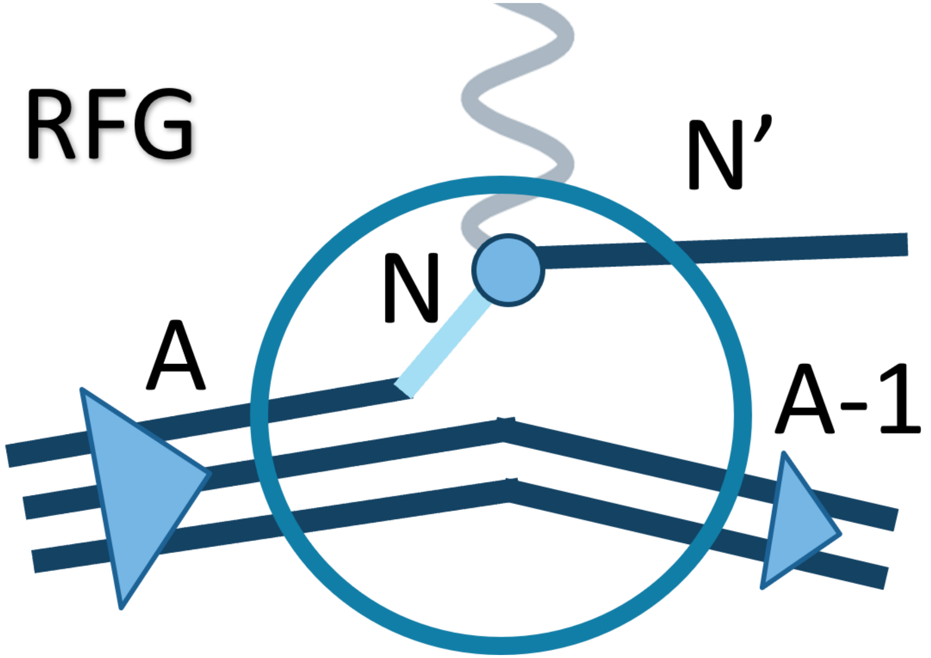
Intermediate RFG*-nucleon approximation

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





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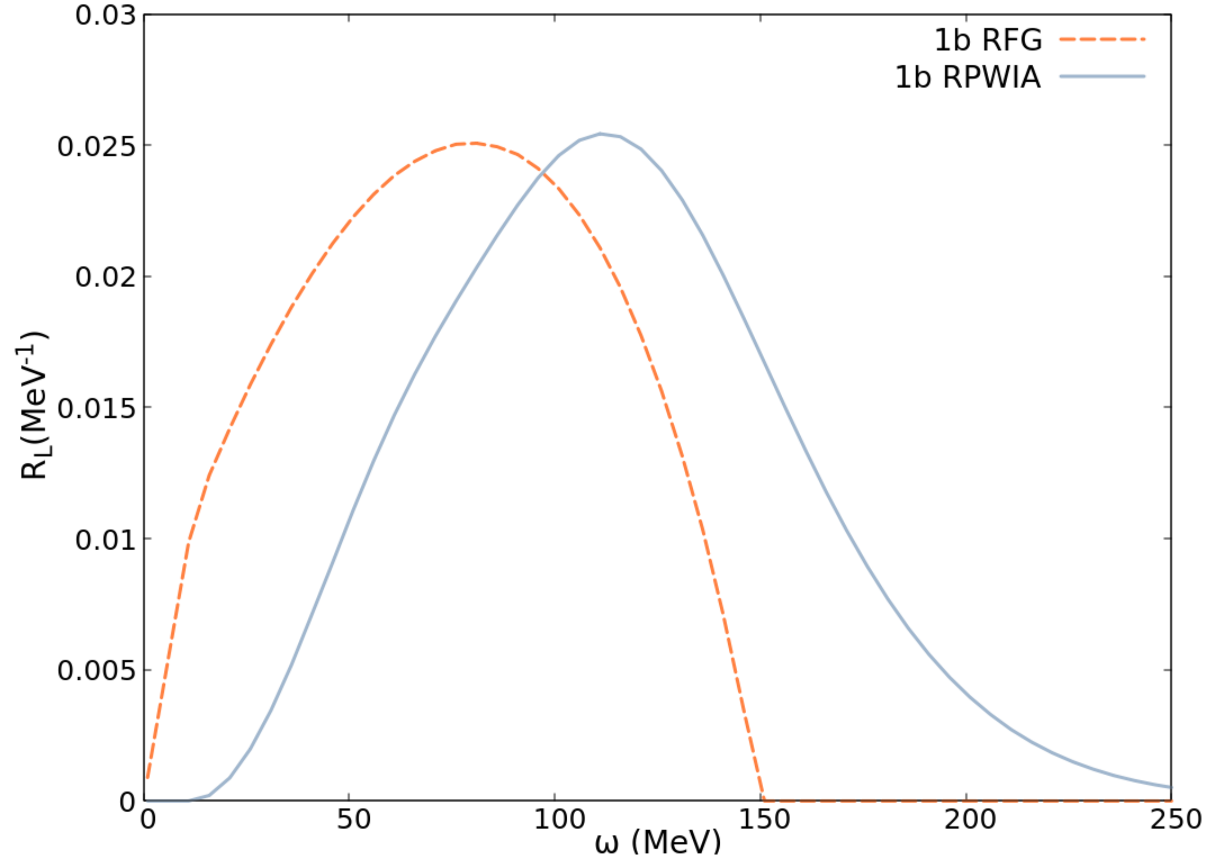

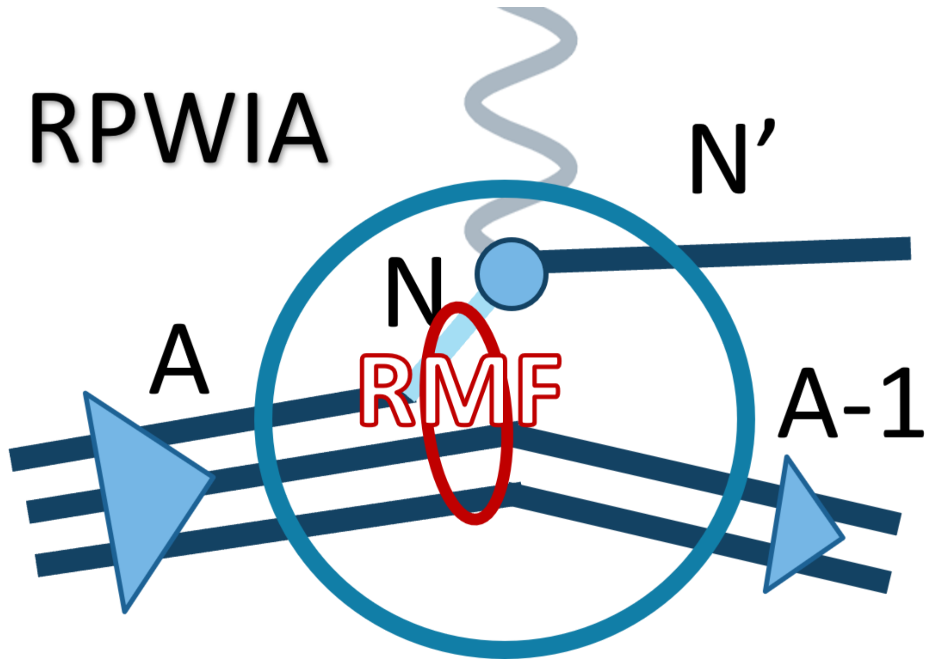

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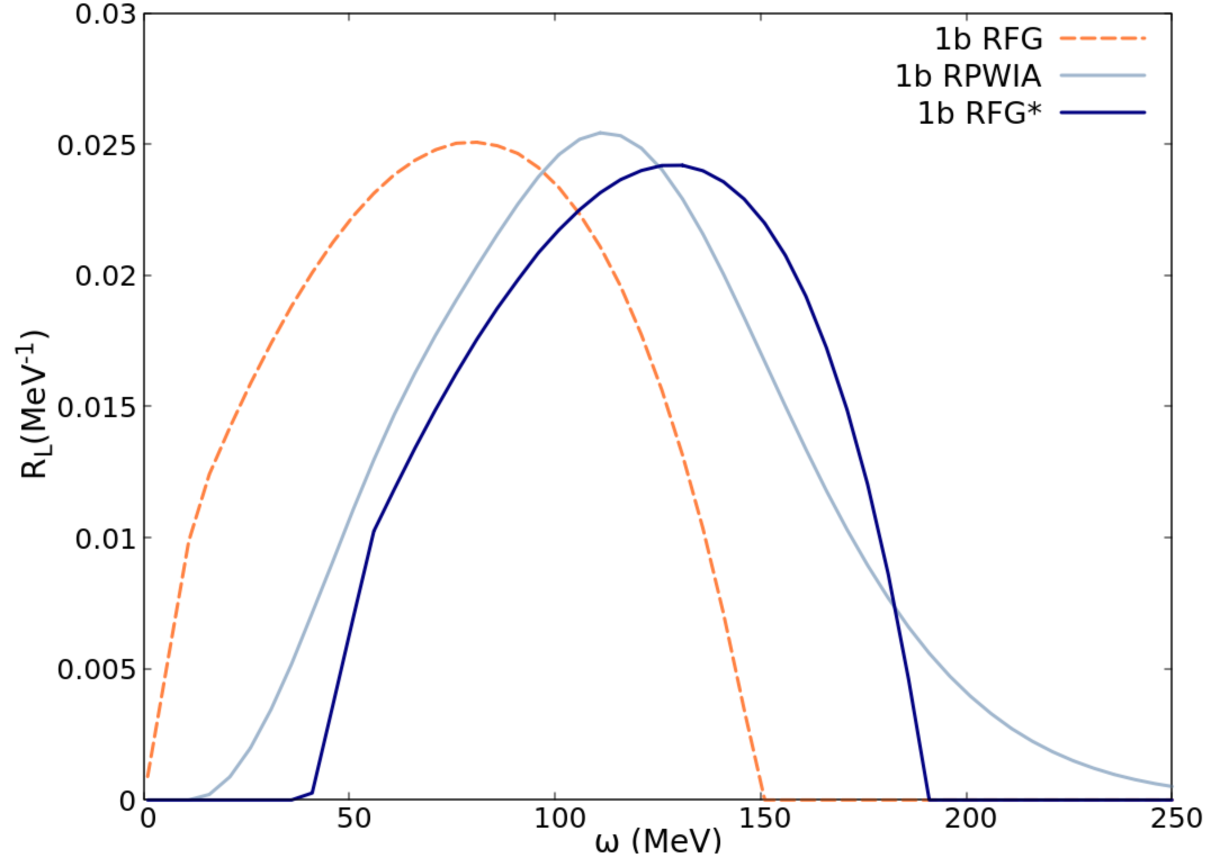

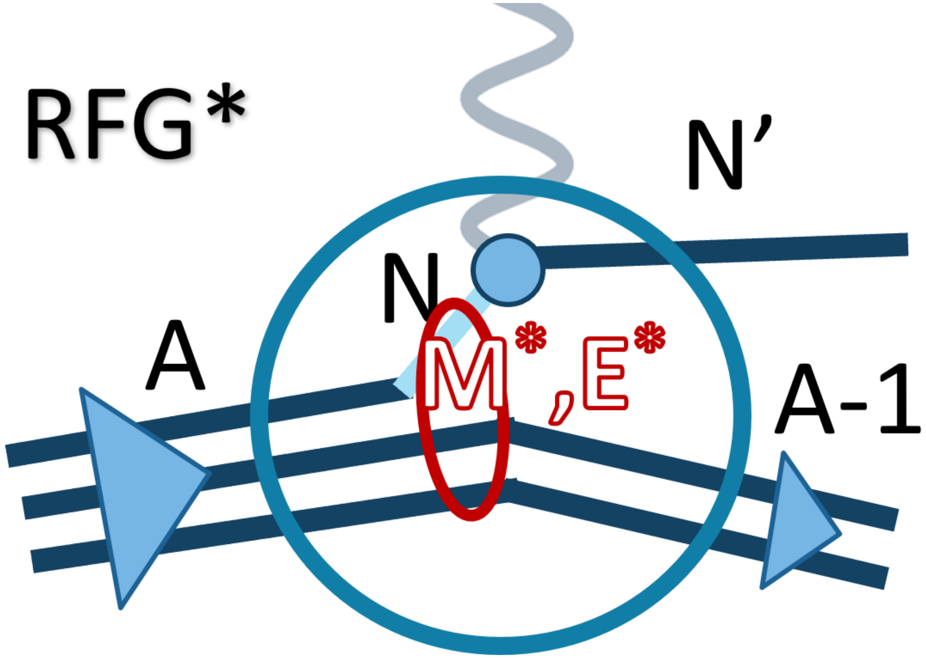

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Intermediate RFG*-nucleon approximation

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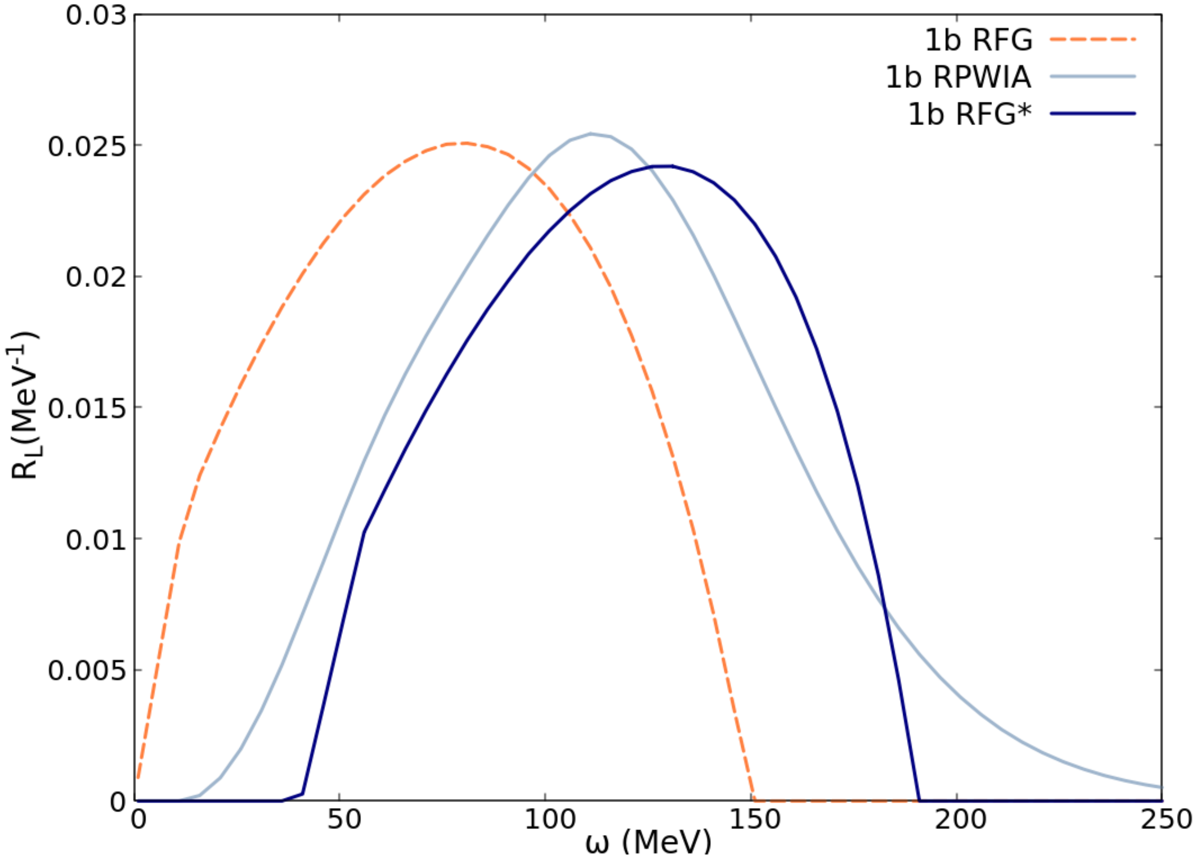

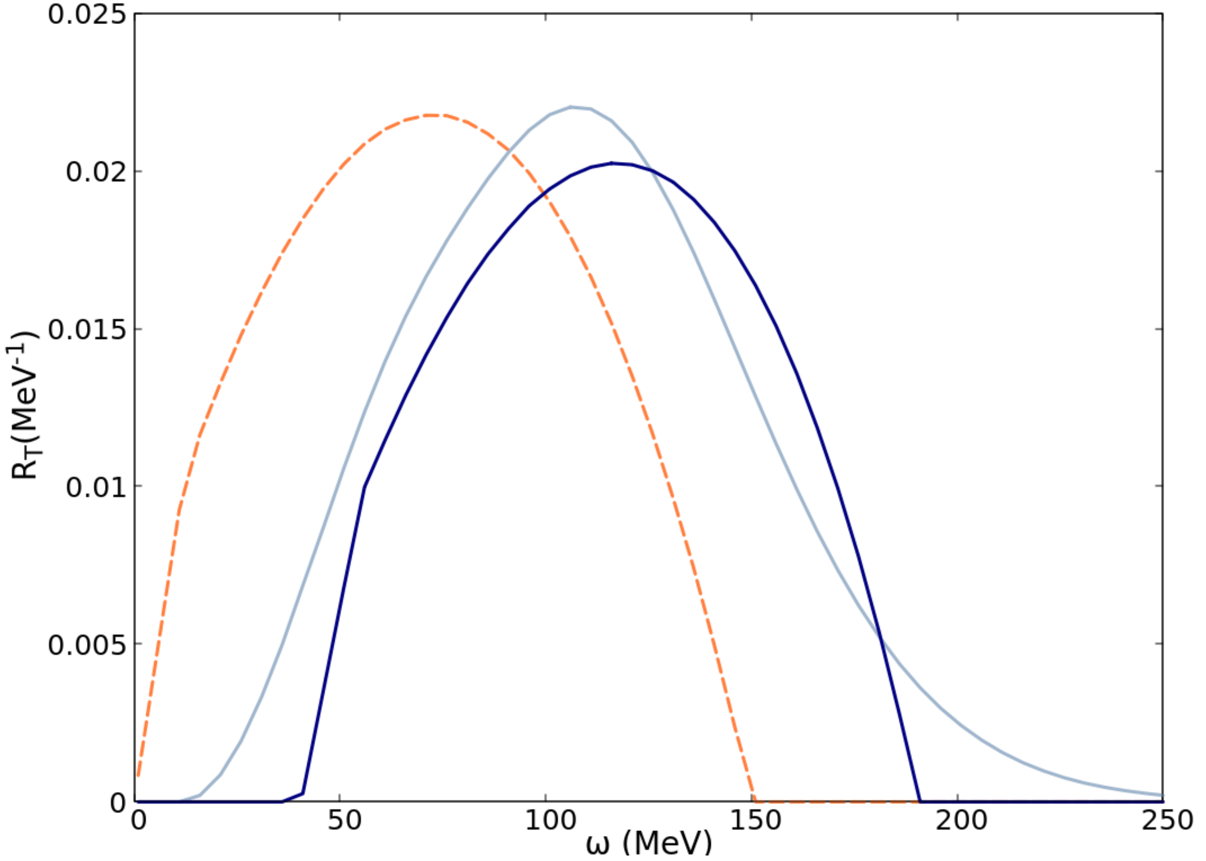

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Intermediate RFG*-nucleon approximation

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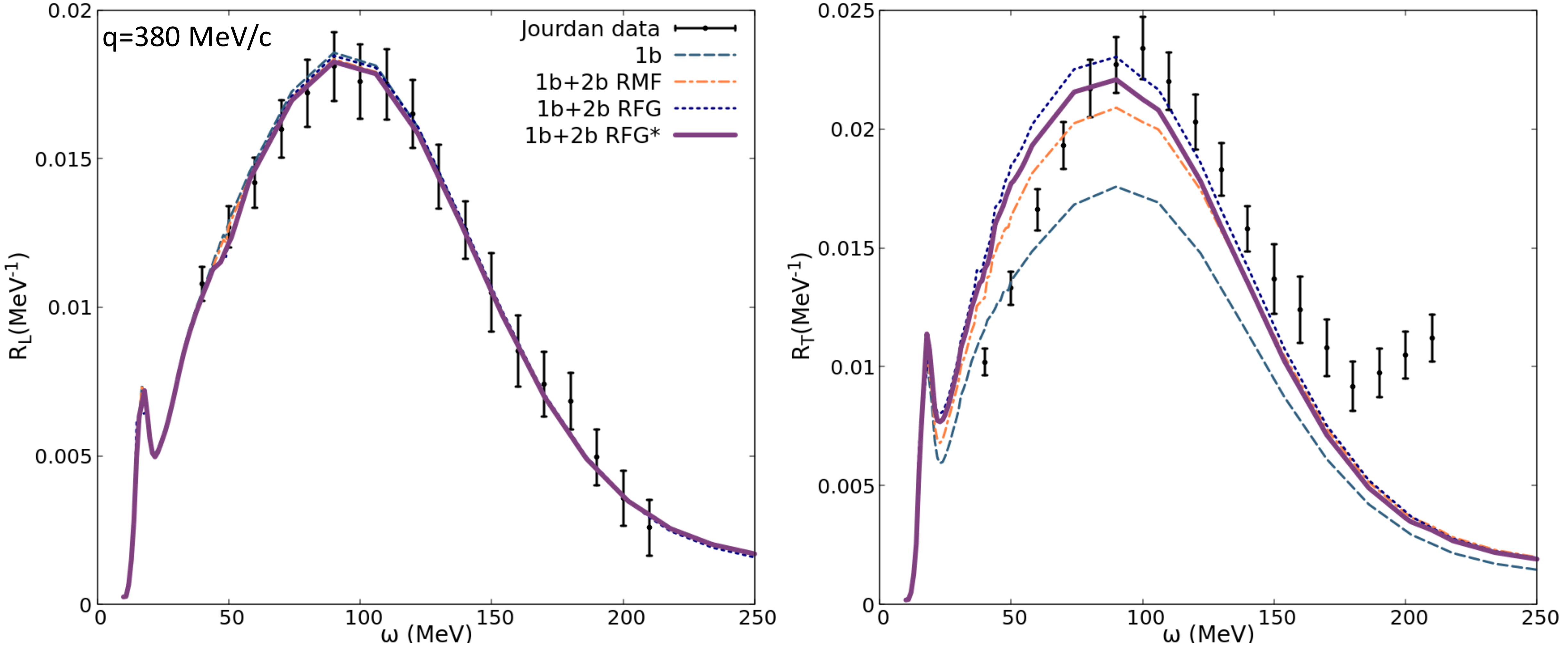

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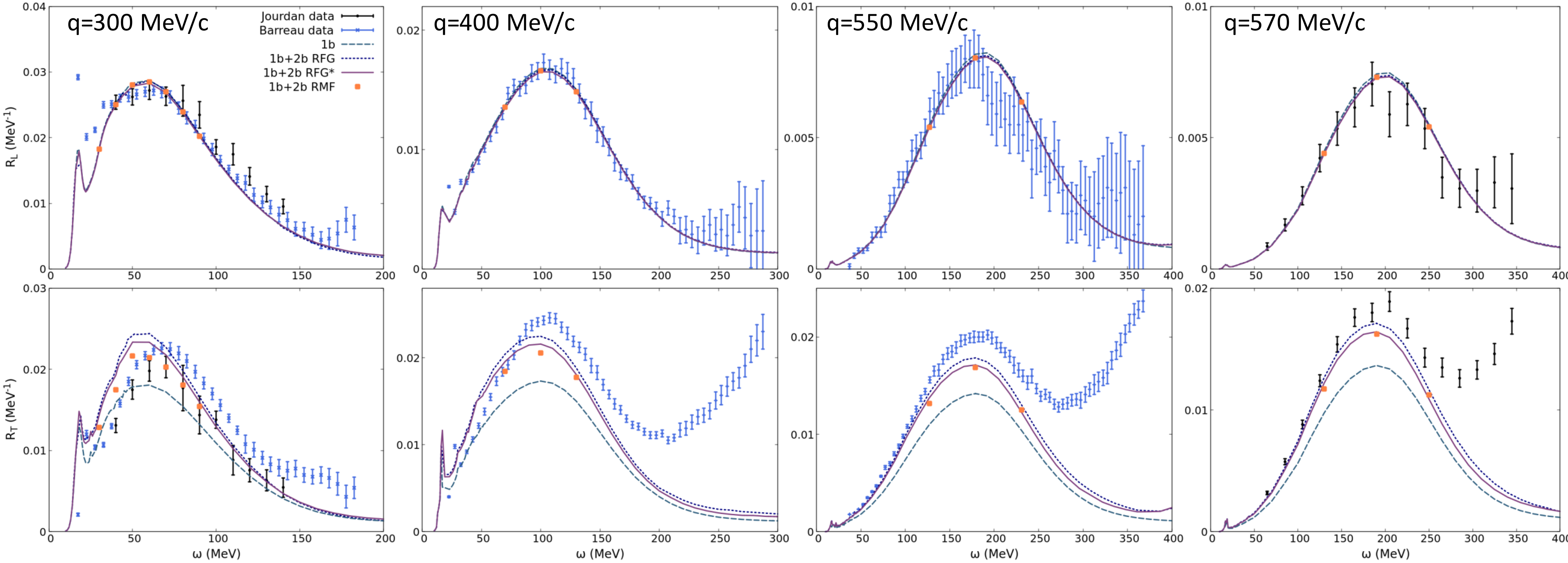

- Essentially identical RFG* and RMF results for momentum transfer around and above **500 MeV/c**.

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