Gesellschaft für Schwerionenforschung, Darmstadt,
Theory Division

Application of the LIT Method to Electromagnetic Reactions with Nuclei: Recent Results

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Workshop@INT Fall-07 Program: “New Approaches in Nuclear Many-Body Theory”, Oct. 15-19

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Application of the LIT Method to Electromagnetic Reactions with Nuclei: Recent Results

Outline

- Photodisintegration of Light Nuclei
  - Six- and Seven-body Reactions with Semirealistic Potentials
  - Realistic Description of ^{4}He Photoabsorption
- Electron Scattering off ^{4}He:
  - Transverse Response Function with a Semirealistic Interaction
  - Longitudinal Response Function with AV18+UIX
- Conclusions and Outlook

LIT + EIHH

Solve the Schrödinger-like equation

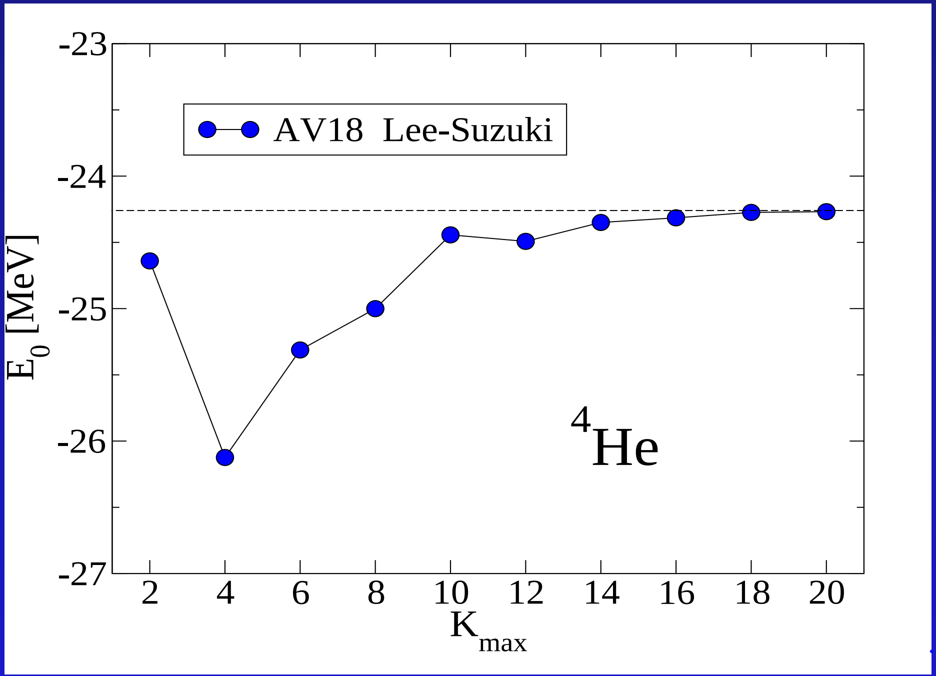
$$(H - E_0 + \sigma)\left|\widetilde{\Psi}\right\rangle = \hat{O}\,|\Psi_0\rangle \quad \text{LIT equation}$$

using an Hyperspherical Harmonics expansion of the w.f.

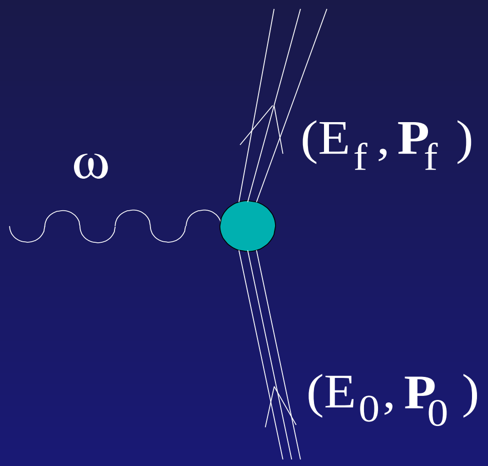
$$\Psi = \sum_{n\;[\mathrm{K}]}^{n_{\max}\;\mathrm{K}_{\max}} c_n^{[\mathrm{K}]} e^{-\frac{\rho}{2}} \rho^{\frac{\nu}{2}} \;L_n^{\nu}(\rho)\; [\mathcal{Y}_{[\mathrm{K}]}^{\mu}(\Omega)\chi_{ST}^{\bar{\mu}}]_{JT}^{a}$$

We define an Effective Interaction according to the Lee-Suzuki method

- Similar to the NCSM, but uses HH basis instead of HO.
- HO parameter dependence
- fast convergence
- can be used for $A > 4$



Photoabsorption of Nuclei



Real Photon

$$|\mathbf{q}| = \omega$$

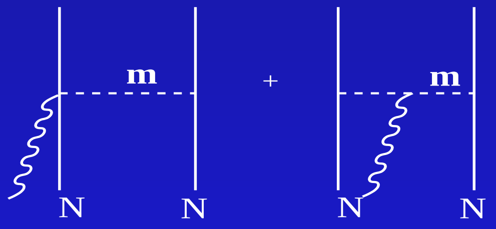
$$\sigma(\omega) = 4\pi^2 \alpha \omega R(\omega)$$

$$R(\omega) = \sum\!\!\!\!\!\!\int_f |\langle \Psi_f | E1 | \Psi_0 \rangle|^2 \, \delta(E_f - E_0 - \omega)$$

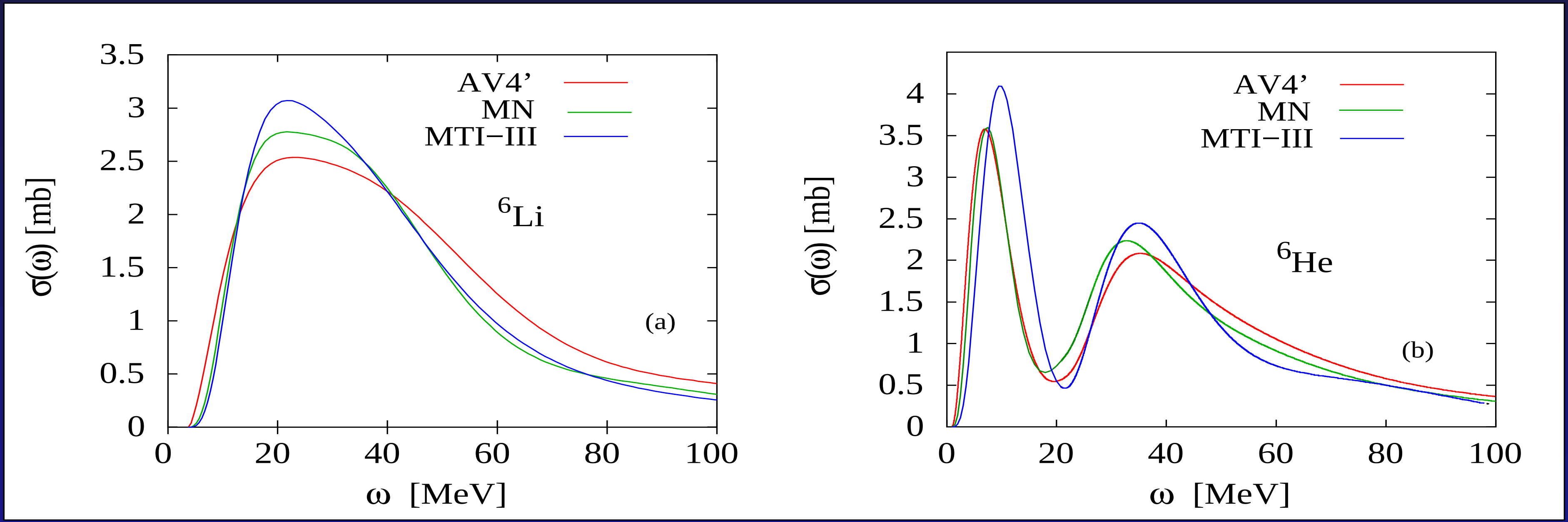
$$E1 = \sum_i^A (\mathbf{r}_i - \mathbf{R}_{\mathrm{CM}}) \frac{1 + \tau_i^3}{2}$$

The MEC are implicitly included in the E1-response via the Siegert theorem

Alternatively....

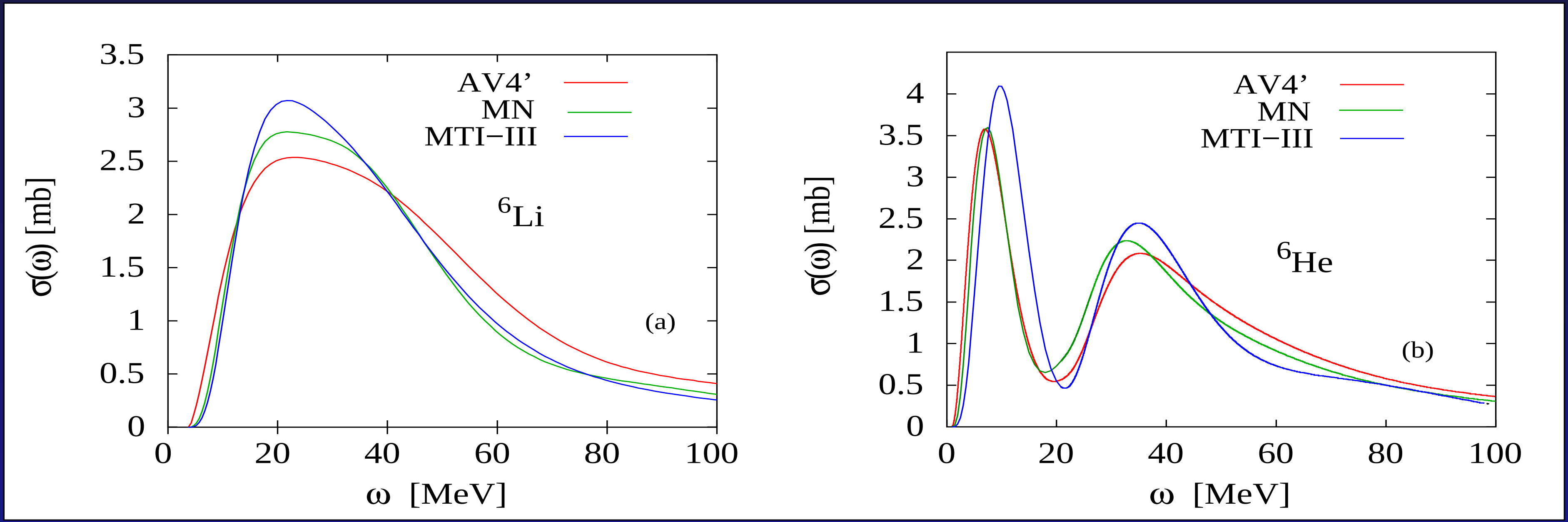


Six-body Photoabsorption



S. B., M. A. Marchisio, N. Barnea, W. Leidemann, G. Orlandini, Phys. Rev. Lett. **89** (2002)

Six-body Photoabsorption



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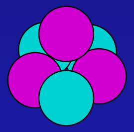
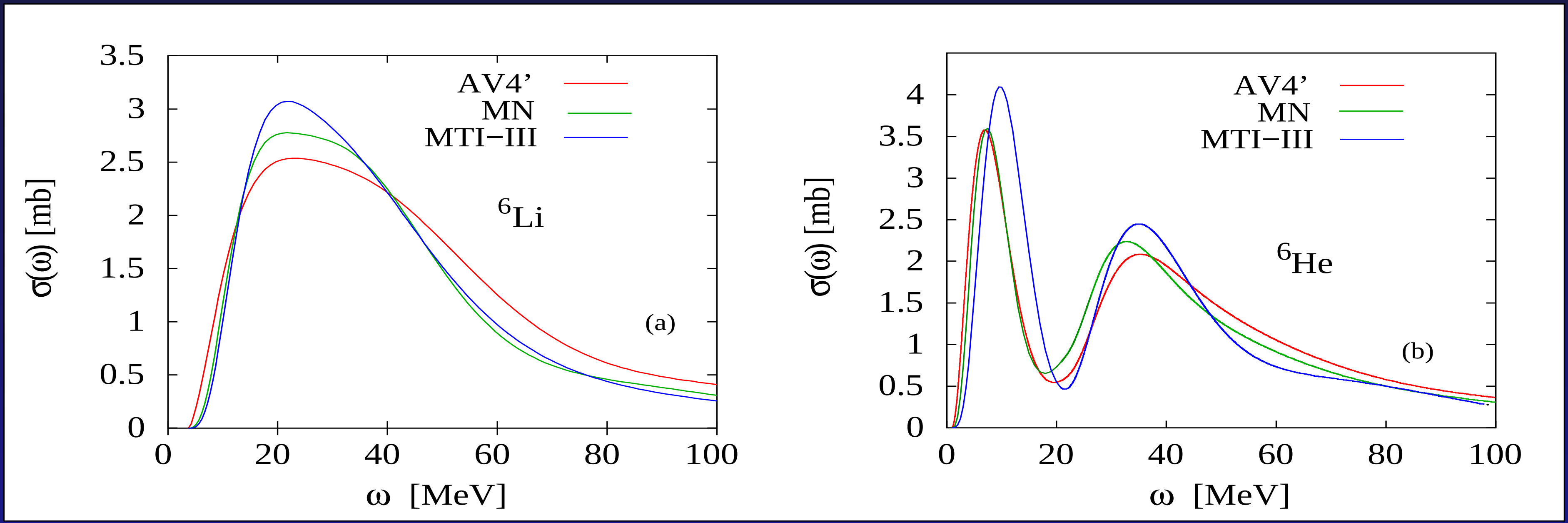
Giant Dipole Mode



^{6}Li

Six-body Photoabsorption



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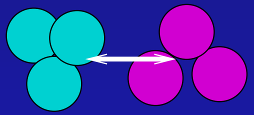
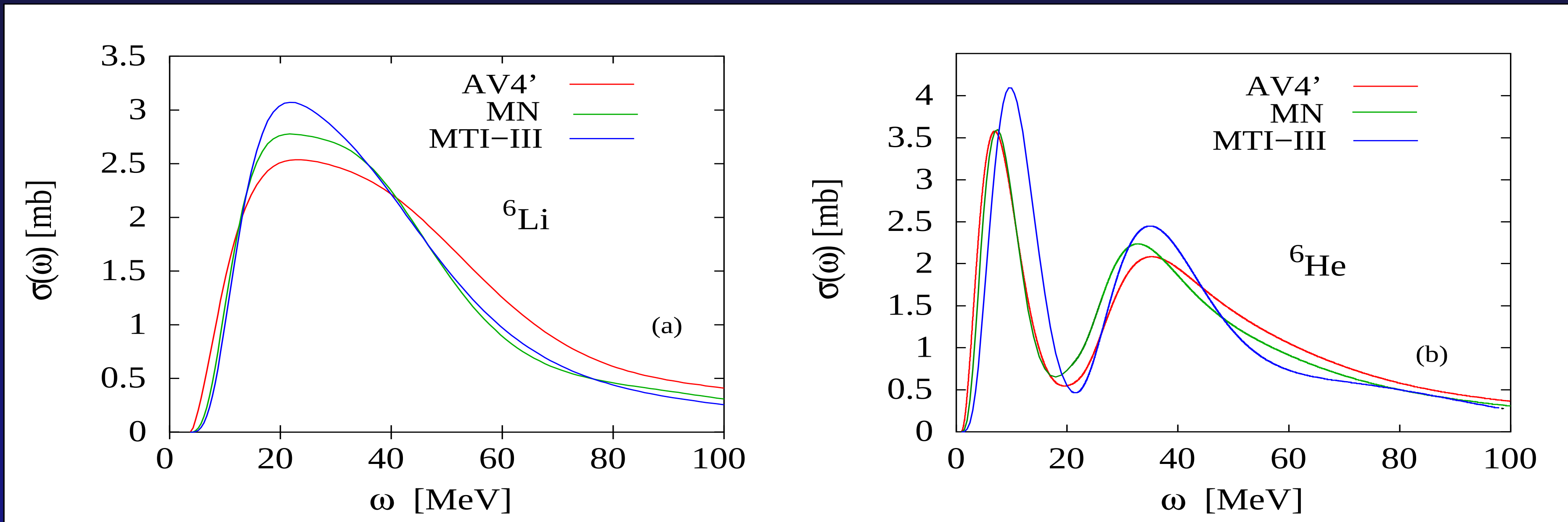


neutrons protons

^{6}Li

Six-body Photoabsorption



S. B., M. A. Marchisio, N. Barnea, W. Leidemann, G. Orlandini, Phys. Rev. Lett. **89** (2002)

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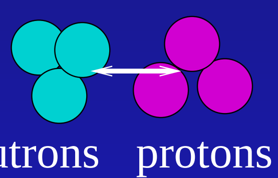
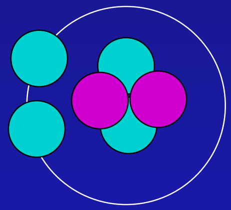


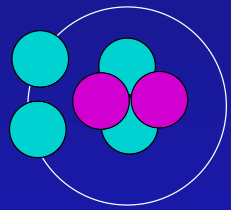
^{6}Li

Soft Dipole Mode



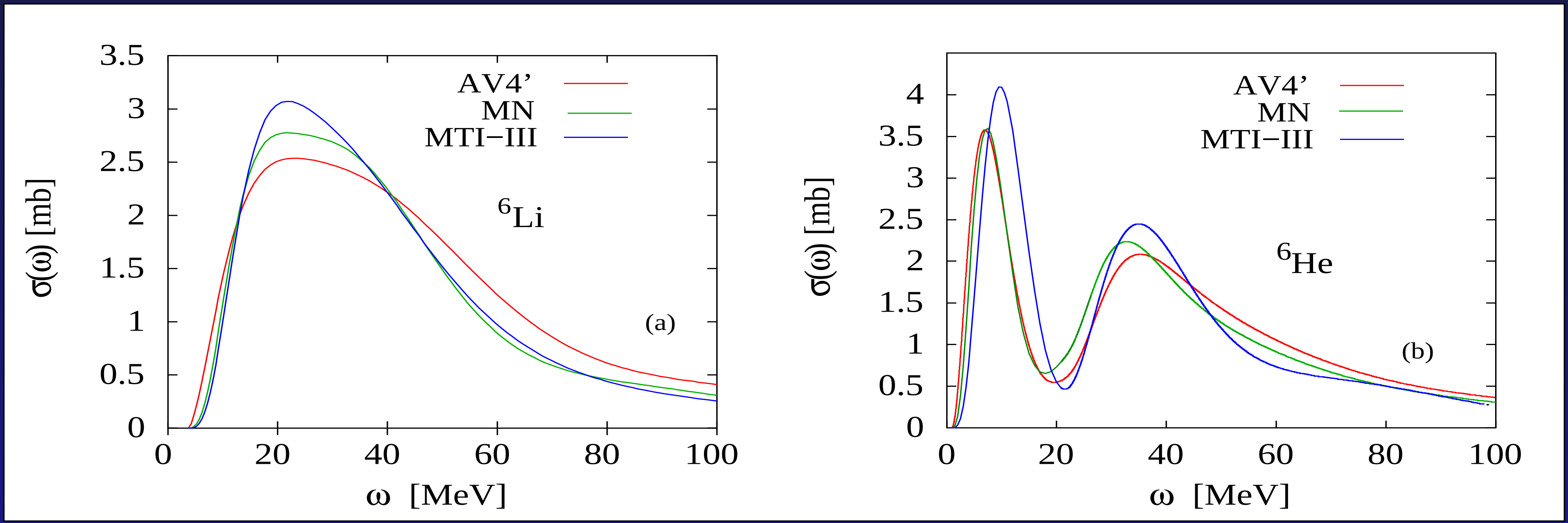
^{6}He

Giant Dipole Mode



^{6}He

Six-body Photoabsorption



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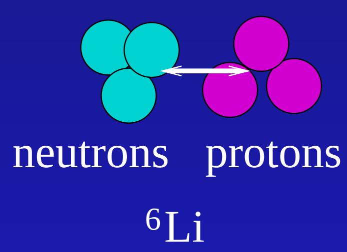
Giant Dipole Mode



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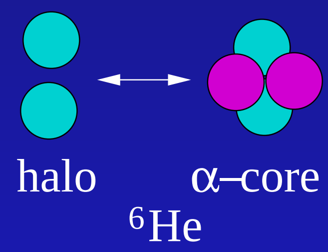

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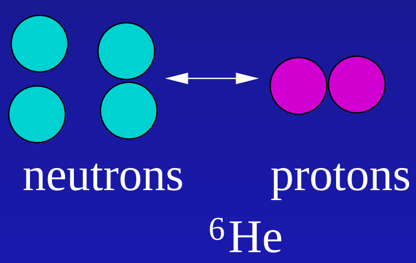

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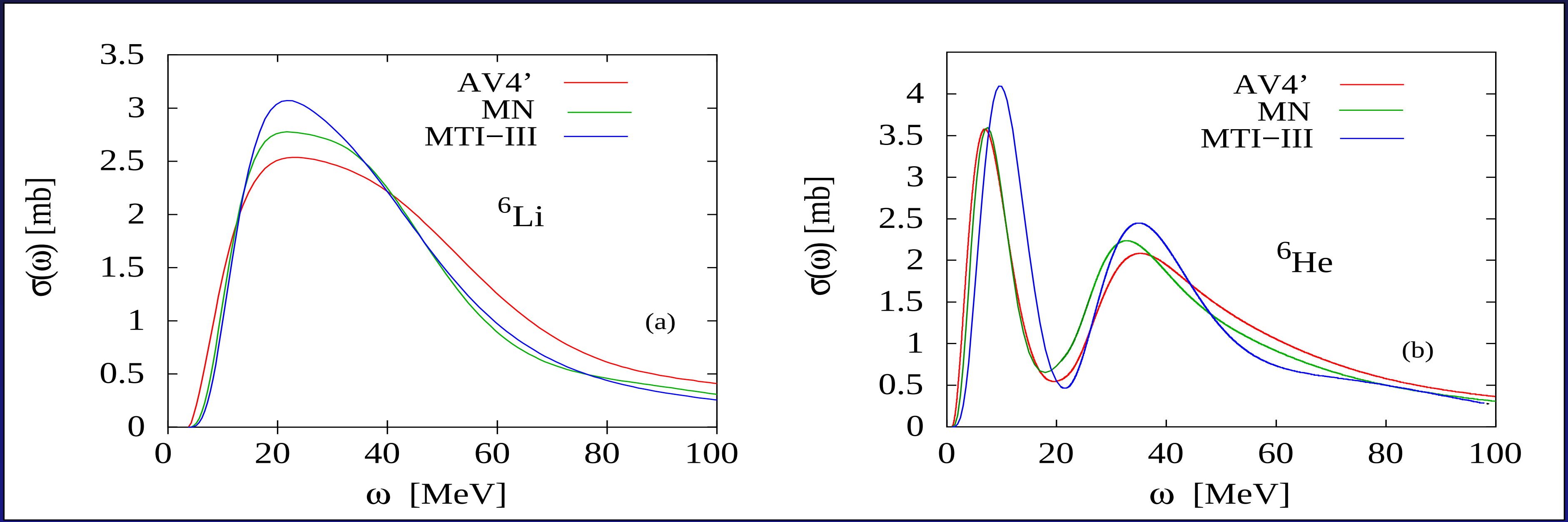

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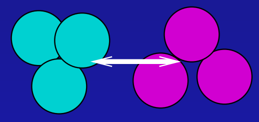

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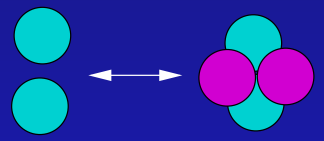

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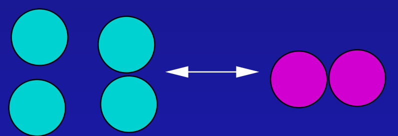
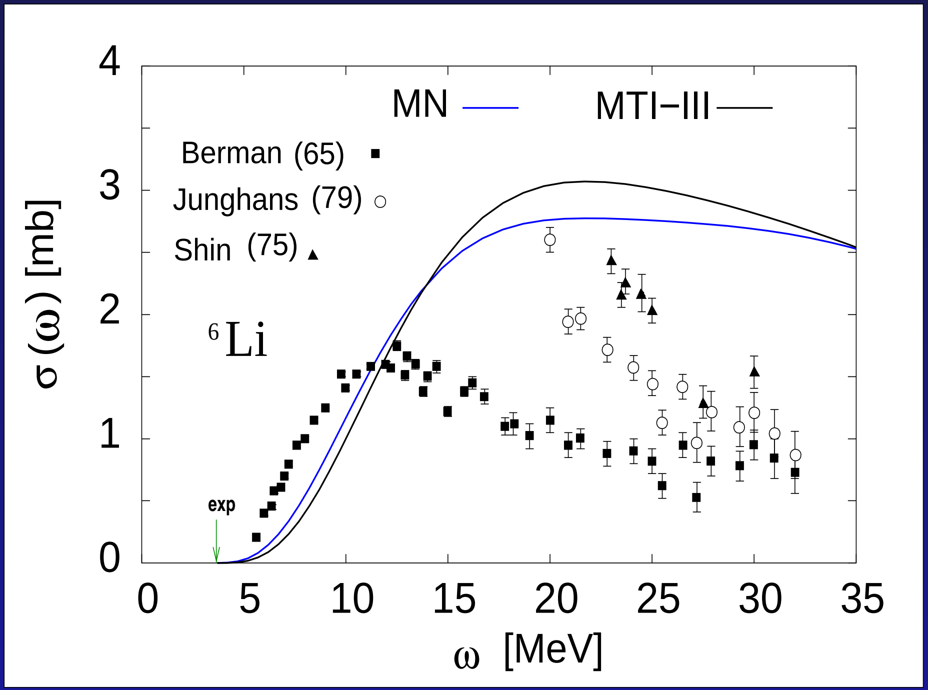
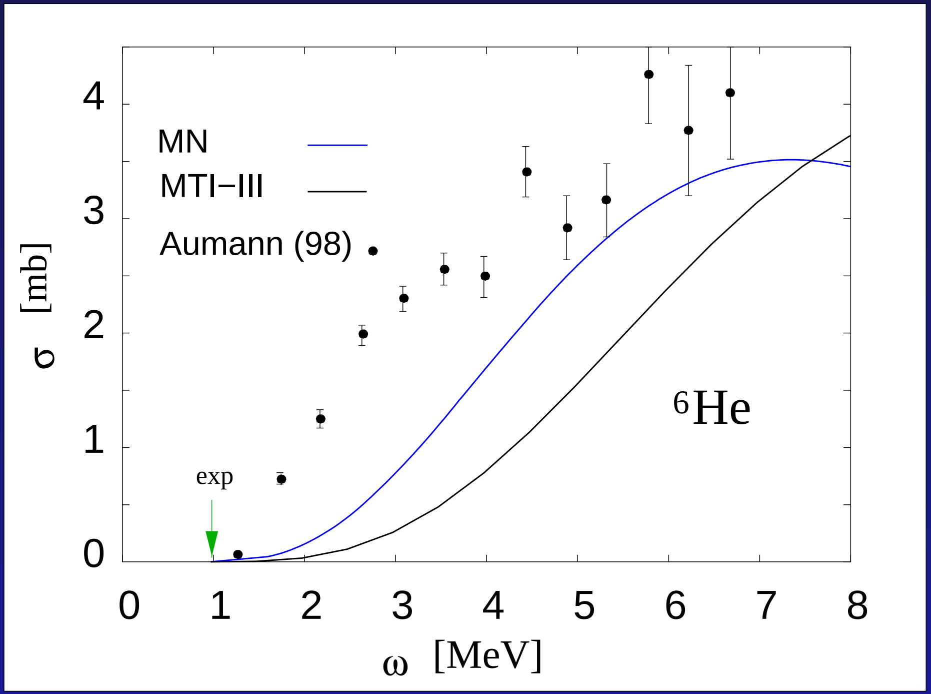


AV4'	$\sqrt{< r^2 >}$ fm	$\sqrt{< r_p^2 >}$ fm
	2.41(5)	1.80(4)
Exp	PRL **93** (2004) 142501	1.912 ± 0.018

Six-body Photoabsorption

Comparison with experiment

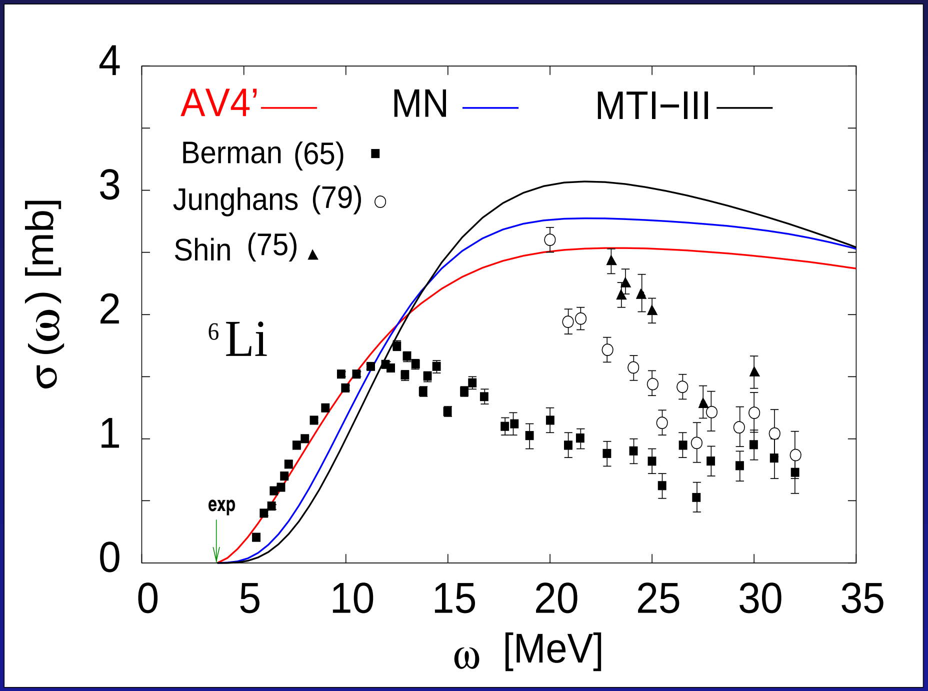


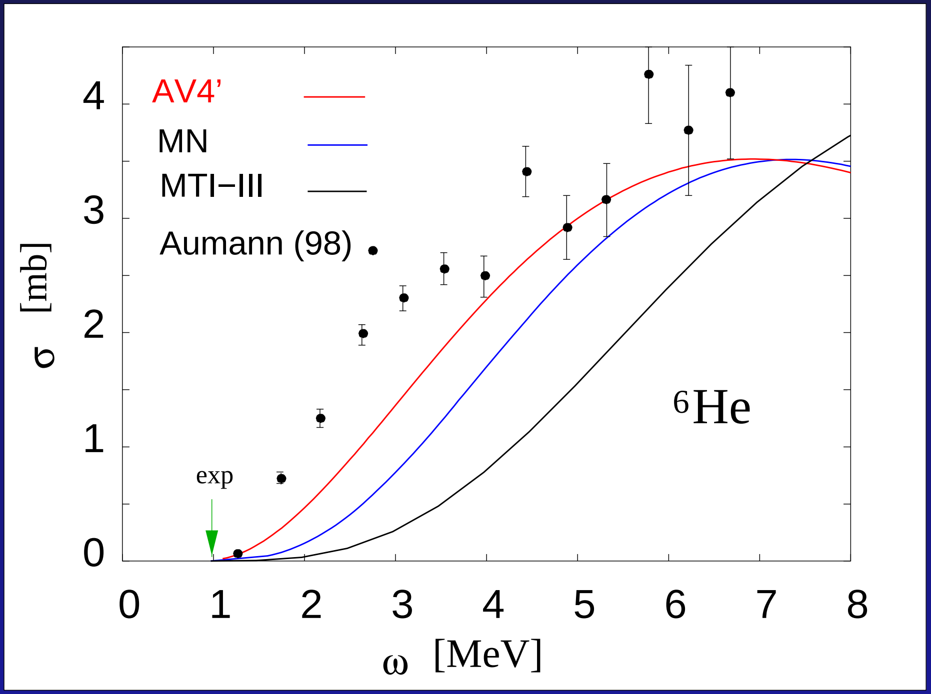


- MTI-III and MN are dominant S-wave potentials (L-even) interactions

Six-body Photoabsorption

Comparison with experiment



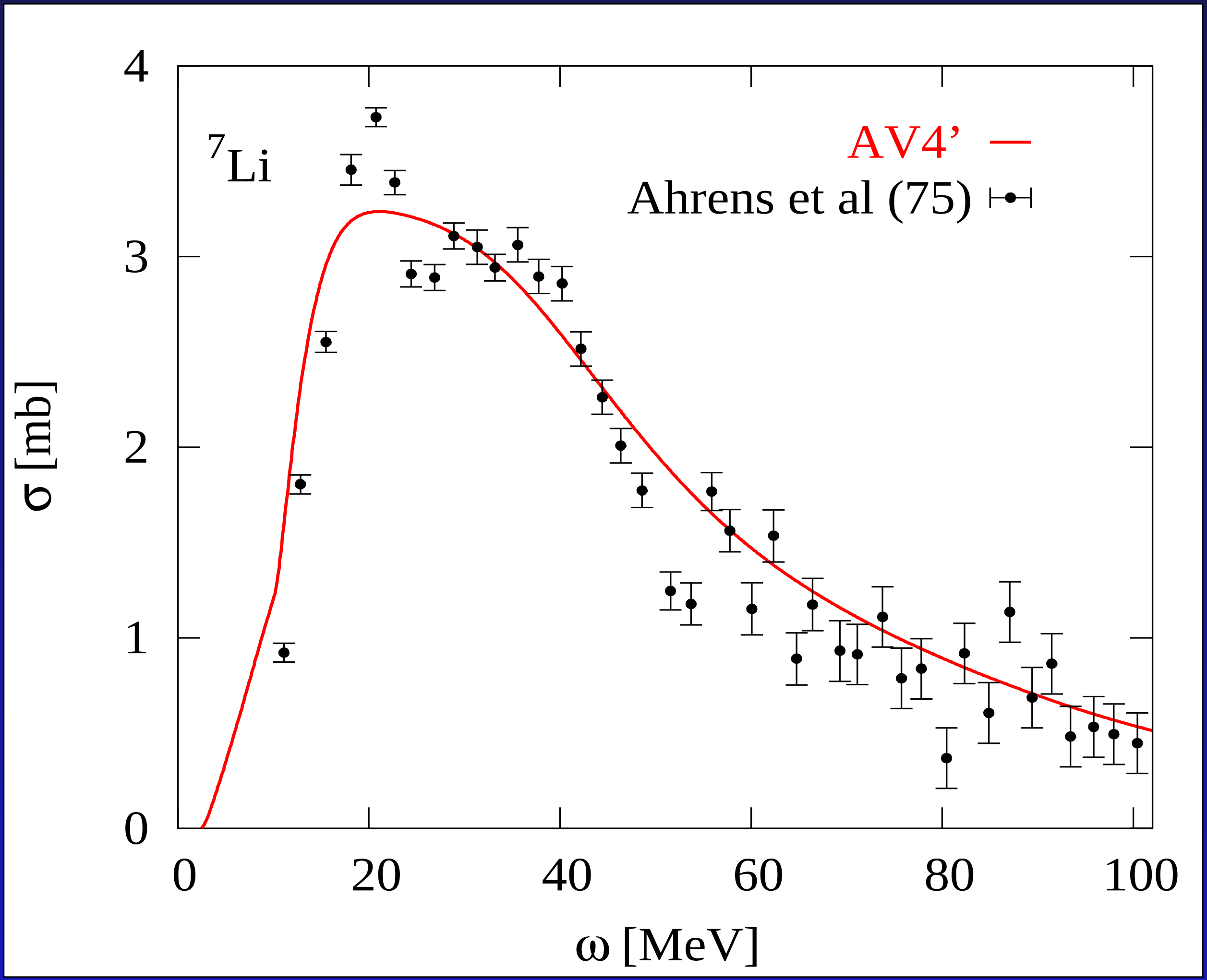


- MTI-III and MN are dominant S-wave potentials (L-even) interactions
- AV4' contains also (L-odd) interactions
  Dominant S- and P-wave Potential

S.B., N. Barnea, W. Leidemann, and G. Orlandini, Phys. Rev. C **69**, 057001 (2004)

Seven-body Photoabsorption

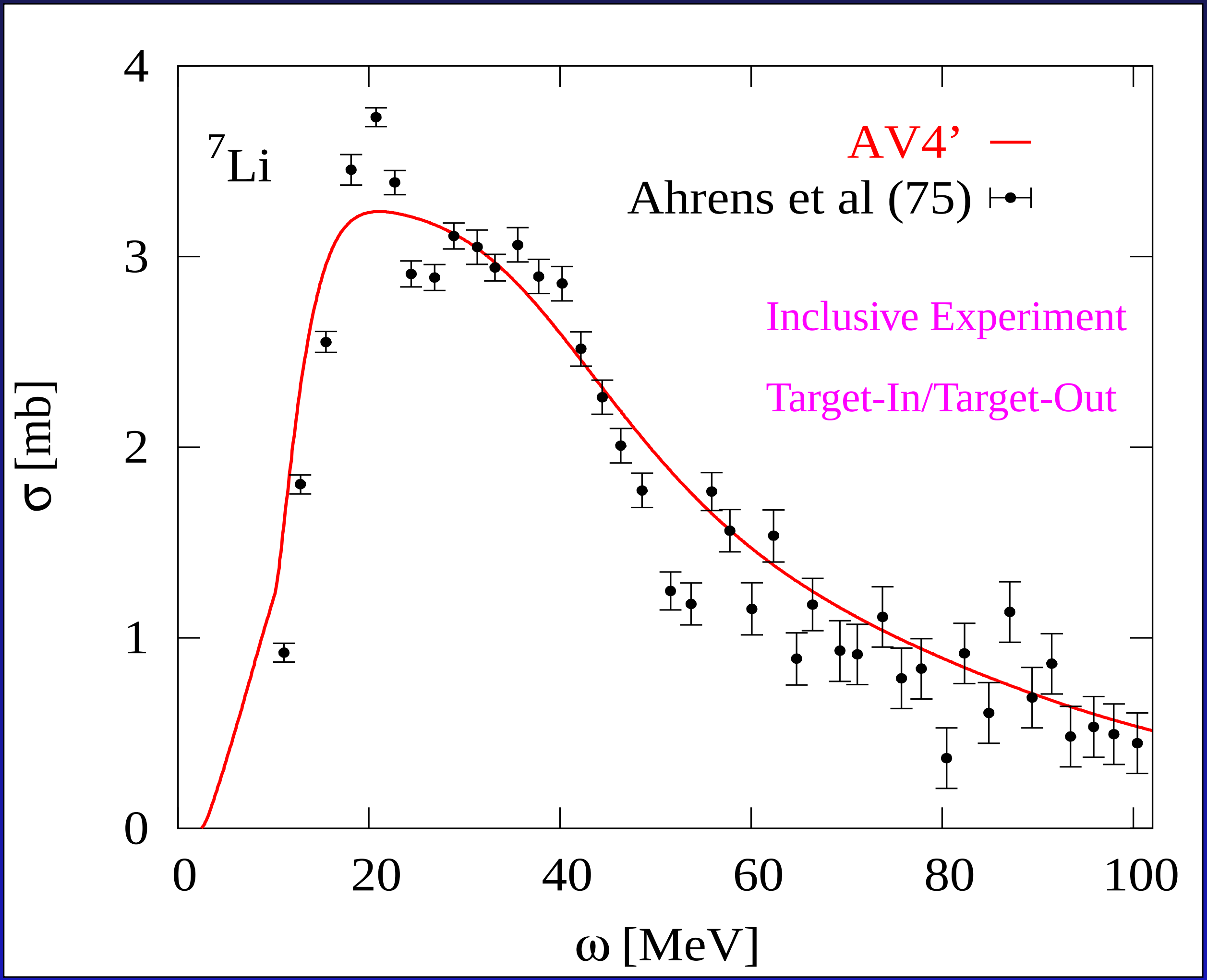
Comparison with experiment



S.B., H. Arenhövel, N. Barnea, W. Leidemann, and G. Orlandini, Phys. Lett. B **603** (2004)

Seven-body Photoabsorption

Comparison with experiment

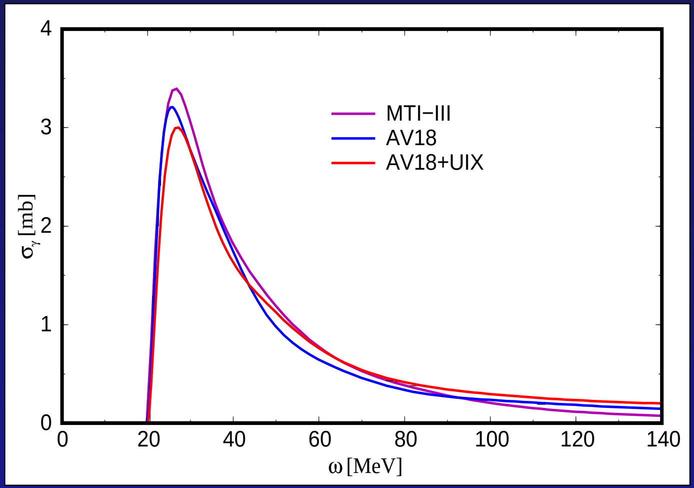


S.B., H. Arenhövel, N. Barnea, W. Leidemann, and G. Orlandini, Phys. Lett. B **603** (2004)

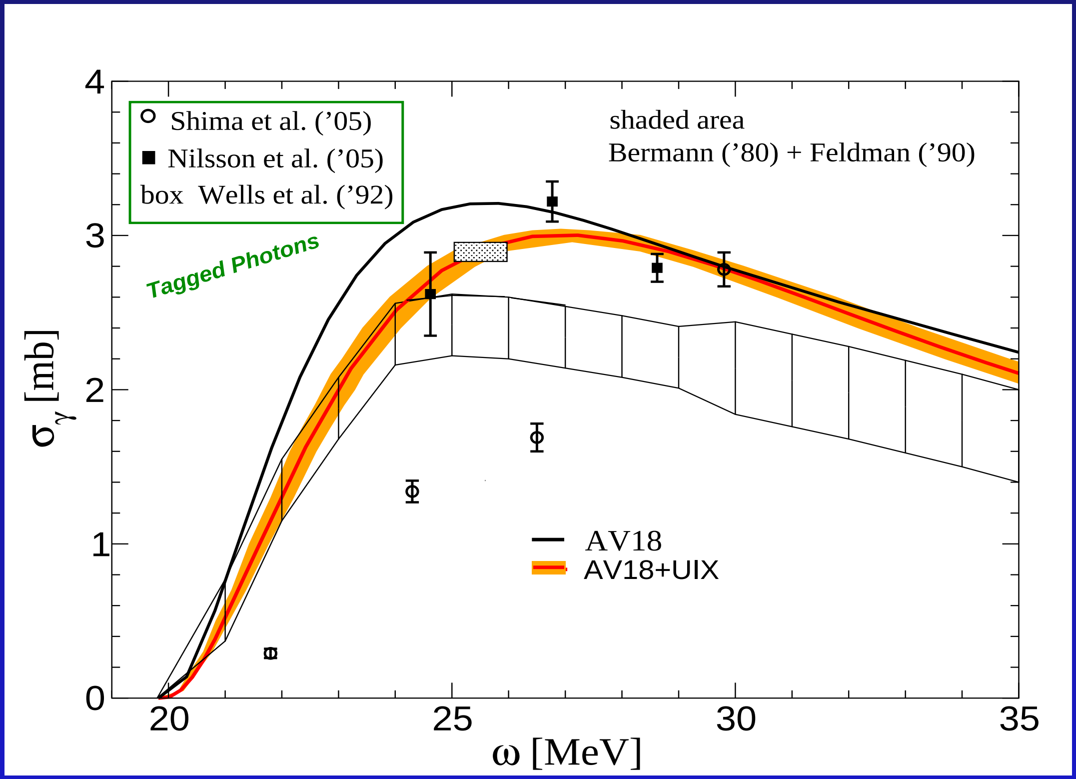
Photodisintegration of the α-particle

Calculation with realistic forces

AV18+UIX   D.Gazit, S.B., N.Barnea, W.Leidemann, G.Orlandini, PRL **96**, 112301 (2006)



- MTI-III overestimates of $10-15\%$ the peak and strongly underestimate the tail
- 3NF lead to a 6% peak damping and 35% tail enhancement



Comparison with experiment improves

when adding 3NF.

Experimental situation should be improved!

Photodisintegration of the α-particle

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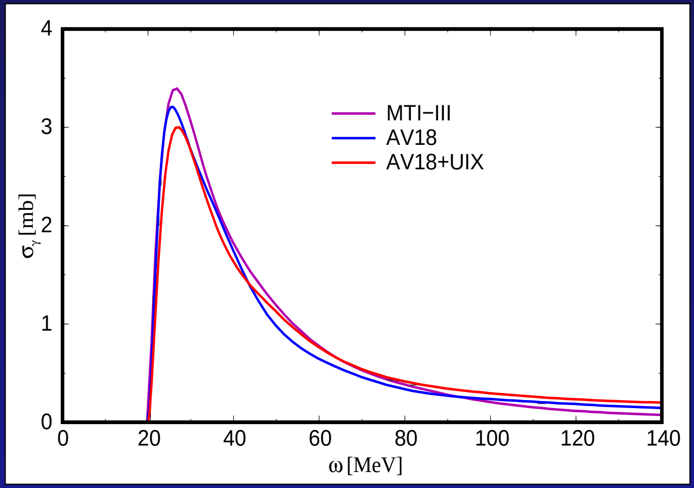

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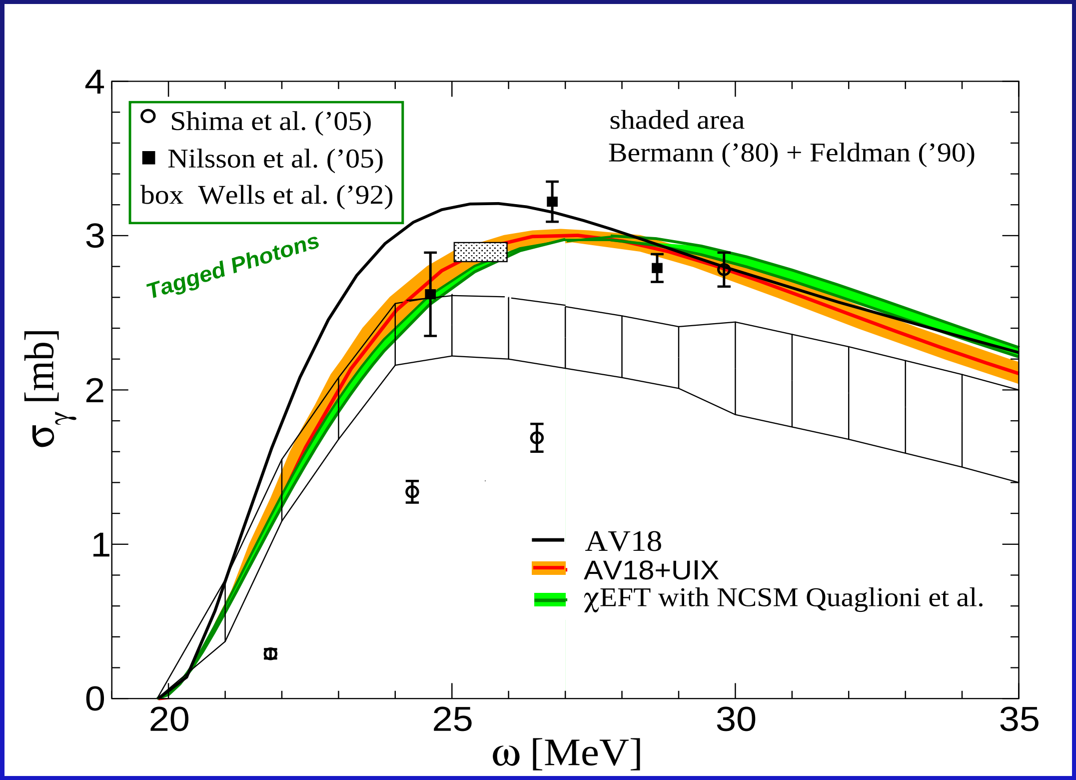

Photodisintegration of the α-particle

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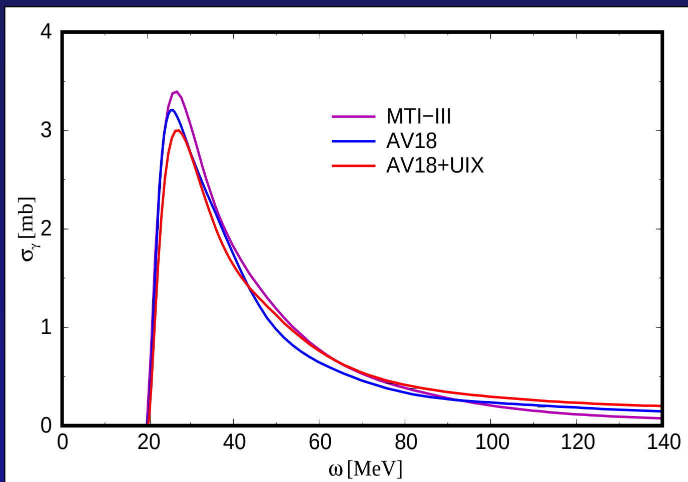

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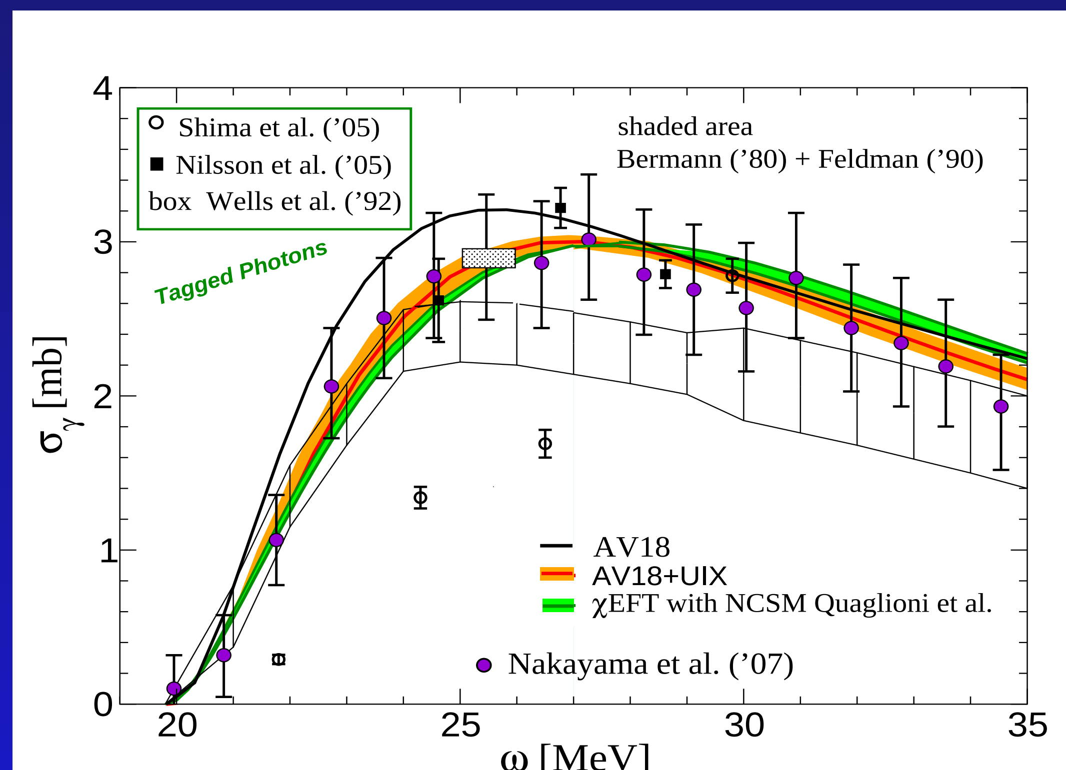


Comparison with experiment improves

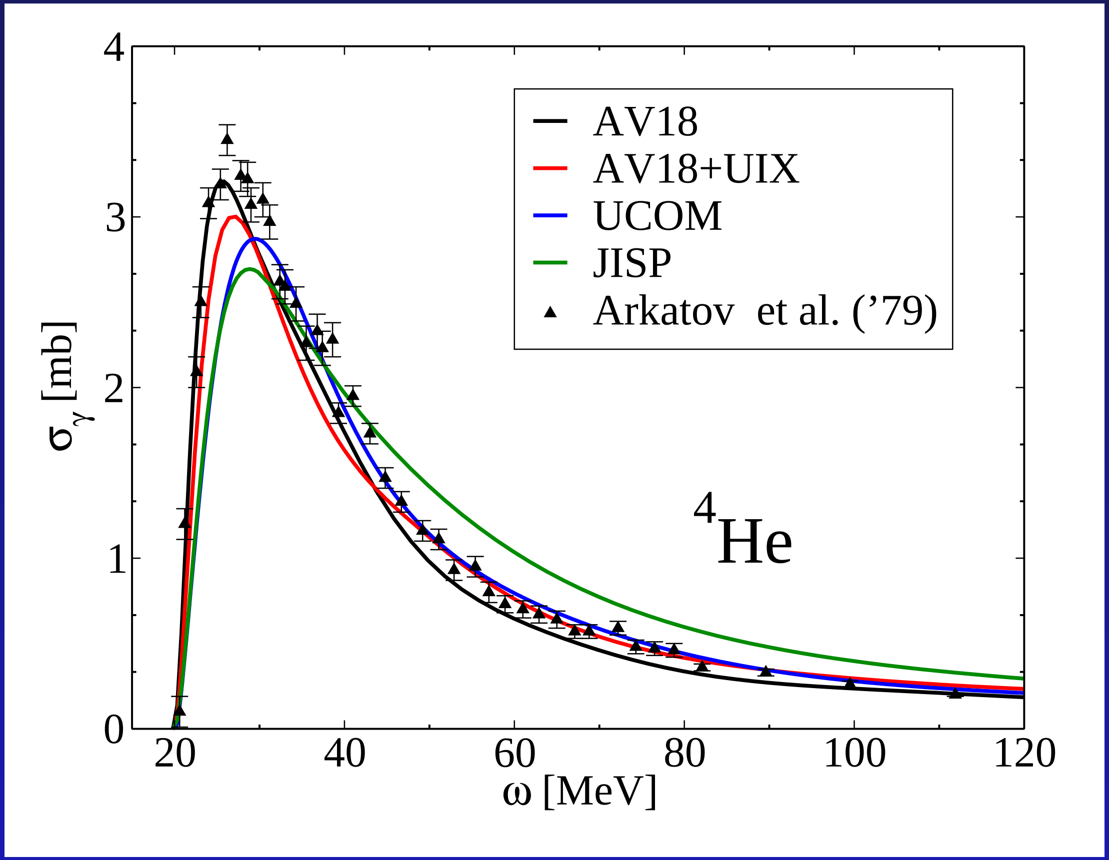
when adding 3NF.

Experimental situation should be improved!

Photodisintegration of the α-particle

Calculation with realistic forces:

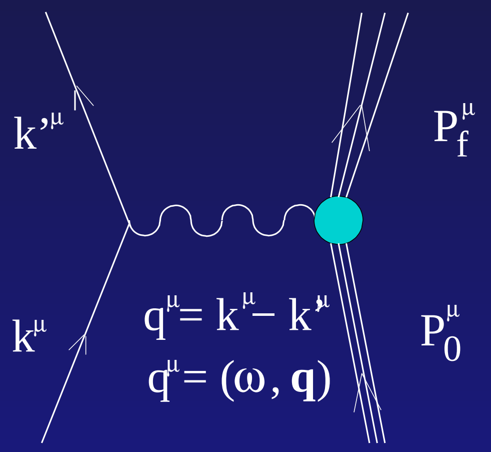
non-local interaction vs. 3NF



JISP N.Barnea, W.Leidemann, G.Orlandini, PRC **74**, 034003 (2006)

UCOM S.B., PRC **75**, 044001 (2007)

Electron Scattering off a nucleus



Virtual Photon

$(\omega, \mathbf{q})$

vary independently

Inclusive Cross Section $A(e,e')X$

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_M \left[\frac{Q^4}{\mathbf{q}^4} R_L(\omega,\mathbf{q}) + \left(\frac{Q^2}{2\mathbf{q}^2} + \tan^2\frac{\theta}{2} \right) R_T(\omega,\mathbf{q}) \right]$$

with $Q^2 = -q_\mu^2 = \mathbf{q}^2 - \omega^2$ and θ scattering angle

and σ_M Mott cross section

Electron Scattering off a nucleus

Longitudinal and transverse response functions can be disentangled via Rosenbluth separation

$$R_L(\omega,\mathbf{q}) = \sum_f |\langle\Psi_f|\,\rho(\mathbf{q})\,|\Psi_0\rangle|^2\,\delta\left(E_f - E_0 - \omega + \frac{\mathbf{q}^2}{2M}\right)$$

$$R_T(\omega,\mathbf{q}) = \sum_f |\langle\Psi_f|\,\mathbf{J}_T(\mathbf{q})\,|\Psi_0\rangle|^2\,\delta\left(E_f - E_0 - \omega + \frac{\mathbf{q}^2}{2M}\right)$$

In a non relativistic framework:

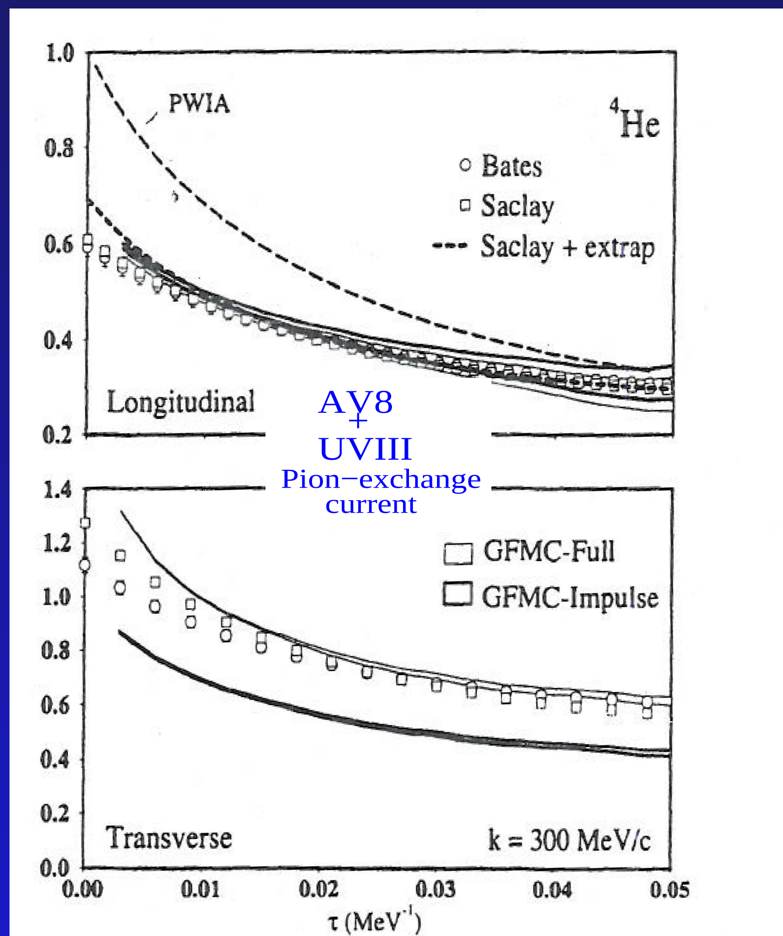
- The charge $\rho(\mathbf{q})$ is a one-body operator $\rho_1(\mathbf{q})$
- The current $\mathbf{J}_T(\mathbf{q})$ includes a one-body operator $\mathbf{J}_1(\mathbf{q})$, spin and convection current, and a two-body operator $\mathbf{J}_2(\mathbf{q})$, the so-called Meson Exchange Current required by gauge invariance

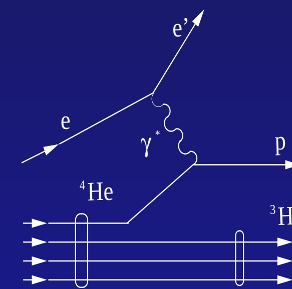
$$\nabla\cdot\mathbf{J}_2(\mathbf{x}) = -i\,[V,\rho_1(\mathbf{x})]$$

Previous Work

For ^{4}He the only realistic calculation with FSI and a consistent MEC is performed with the Laplace Transform using GFMC

J. Carlson and R. Schiavilla, PRC **49**, R2880 (1994)

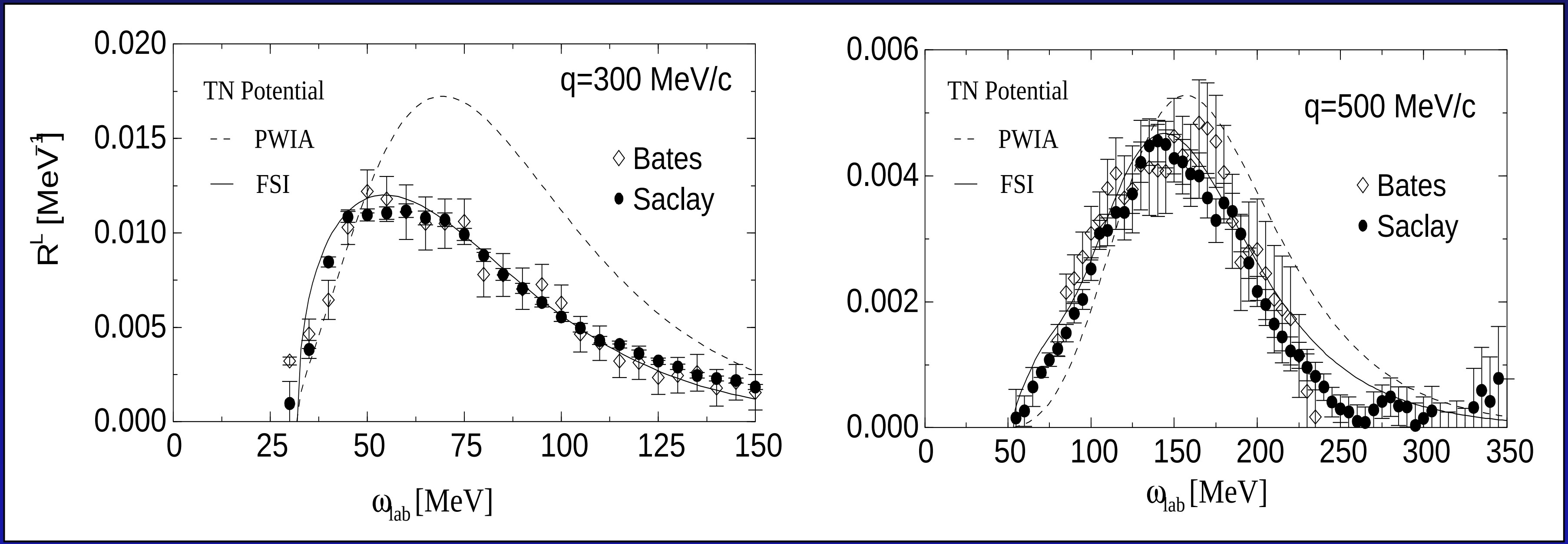




Previous Work

Calculation for ^{4}He with the LIT method and CHH

Semirealistic TN potential

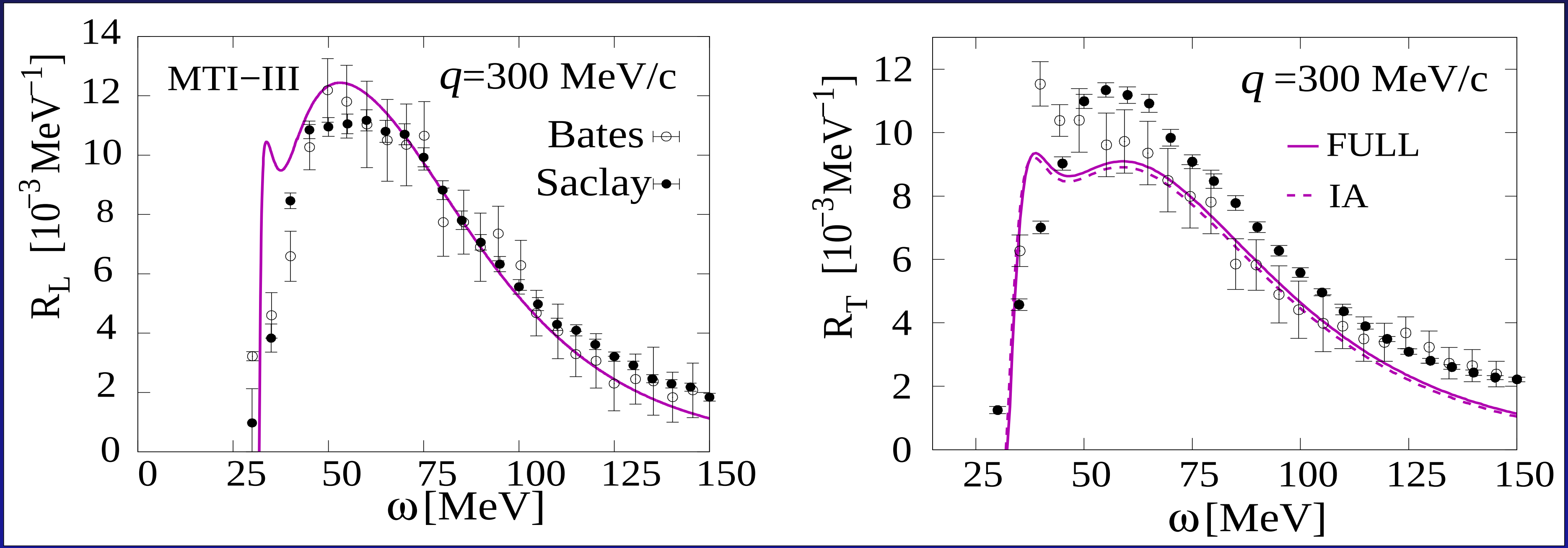


V. E. Efros, W. Leidemann and G. Orlandini, PRL **78**, 432 (1997).

Confirms the importance of FSI to correctly describe the reaction mechanism!

Electron Scattering with the LIT

Electron scattering off ^{4}He with a semirealistic forces



S.B., H.Arenhövel, N. Barnea, W. Leidemann, G. Orlandini, PRC **76**, 014003 (2007)

MTI-III leads to a reasonable description of R_L

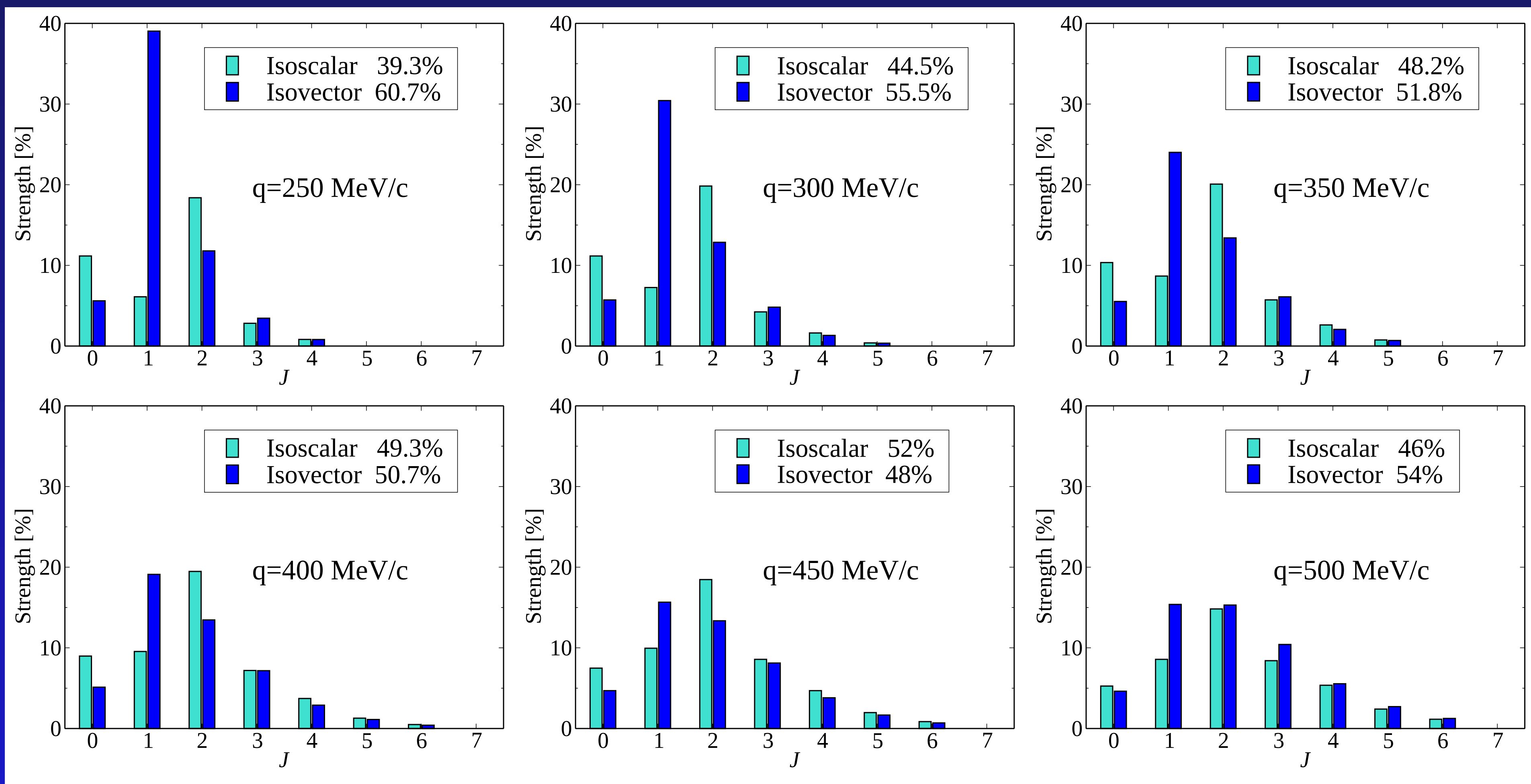
Small effect of MEC in R_T probably due to missing π-exchange

Longitudinal Response Function: AV18

$$\rho_{(1)}(\boldsymbol{q},\omega) = \sum_k G_E^S(Q^2) e^{i\mathbf{q}\cdot\mathbf{r}'_k}\frac{1}{2} + G_E^V(Q^2) e^{i\mathbf{q}\cdot\mathbf{r}'_k}\frac{\tau_k^3}{2}, \text{ with } G_E^{S/V} = G_E^p \pm G_E^n$$

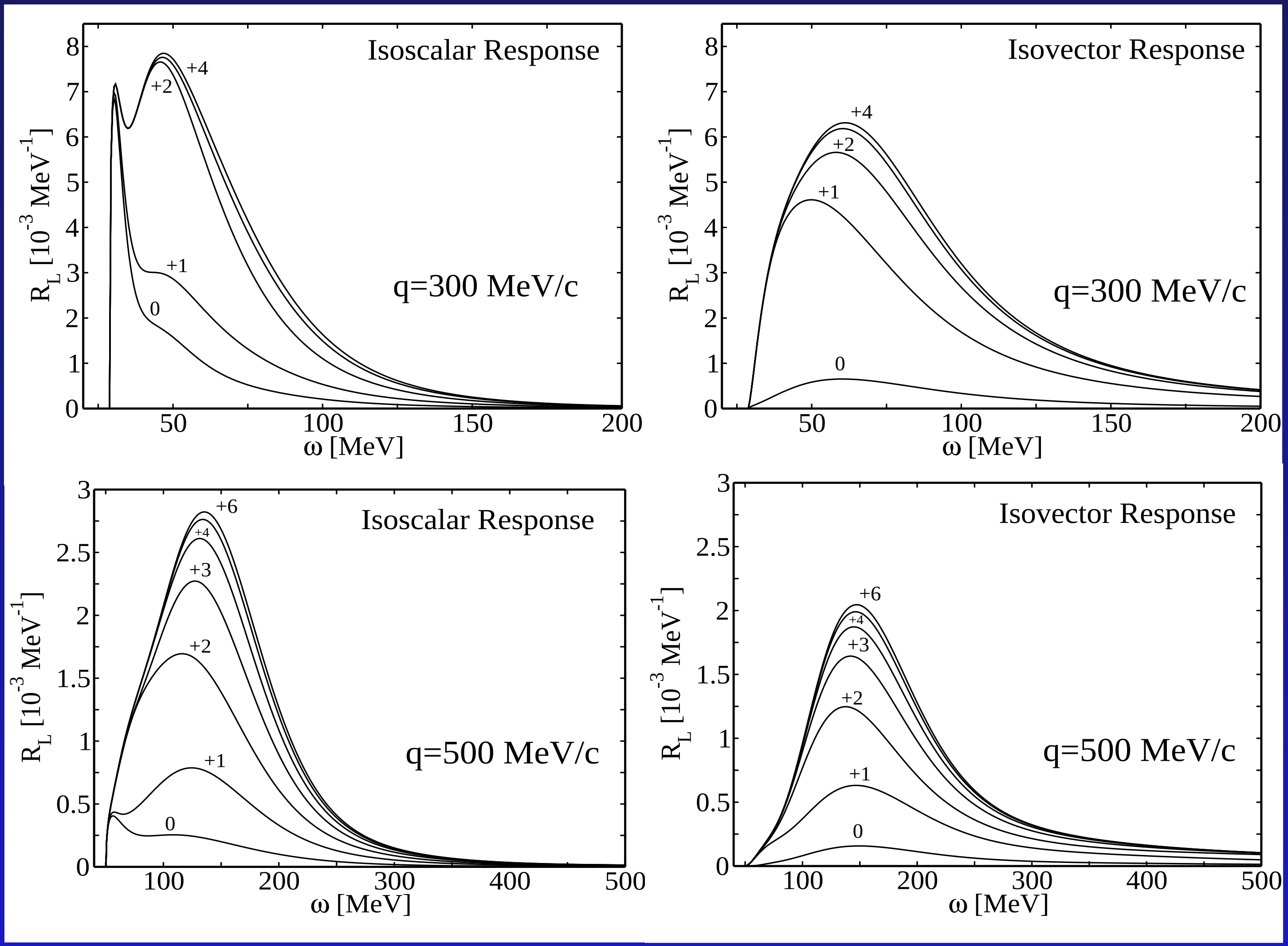
$$\rho_{(1)}(\boldsymbol{q}) = \sum_J C_J^S(\boldsymbol{q}) + C_J^V(\boldsymbol{q})$$

Distribution of the total strength among the multipoles



Longitudinal Response Function: AV18

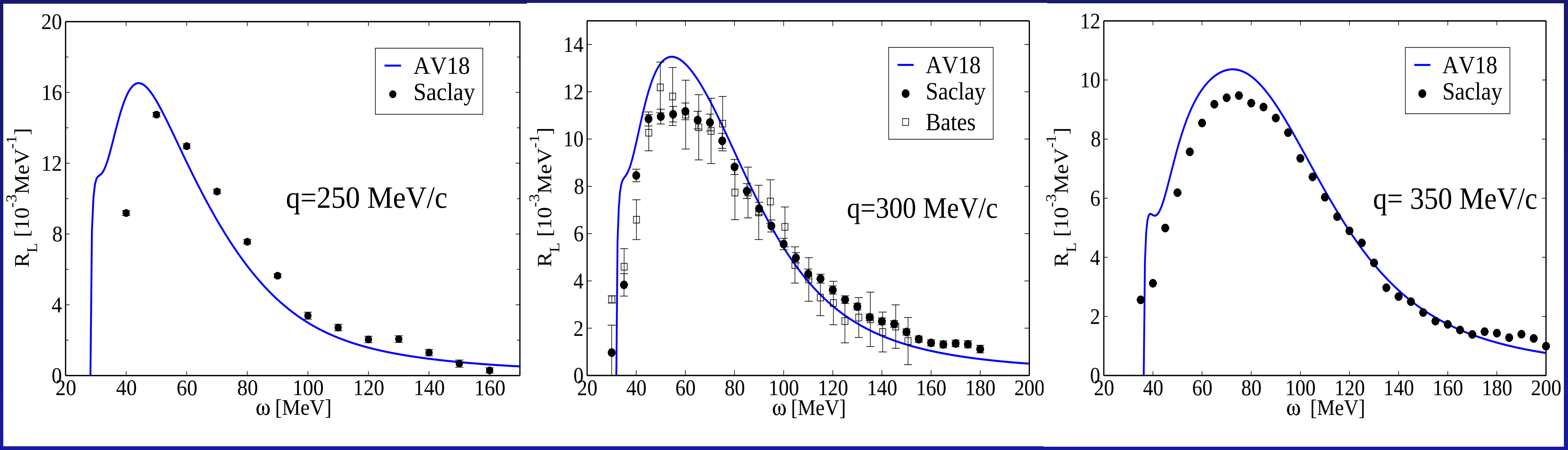
Distribution of the multipole strengths as function of the energy



Longitudinal Response Function:AV18

Comparison with experiment

Medium-low momentum transfer

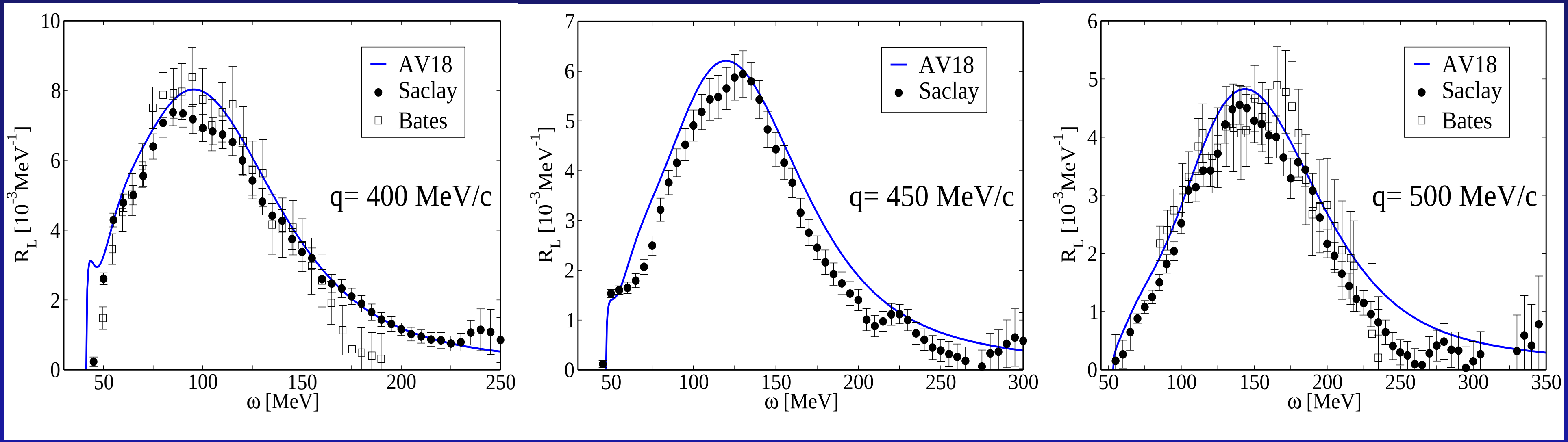


- With AV18 we find larger strength with respect to the experiment in the q.e. peak region.
- The shoulder at threshold is due to isoscalar monopole transition.

Longitudinal Response Function:AV18

Comparison with experiment

Medium-high momentum transfer

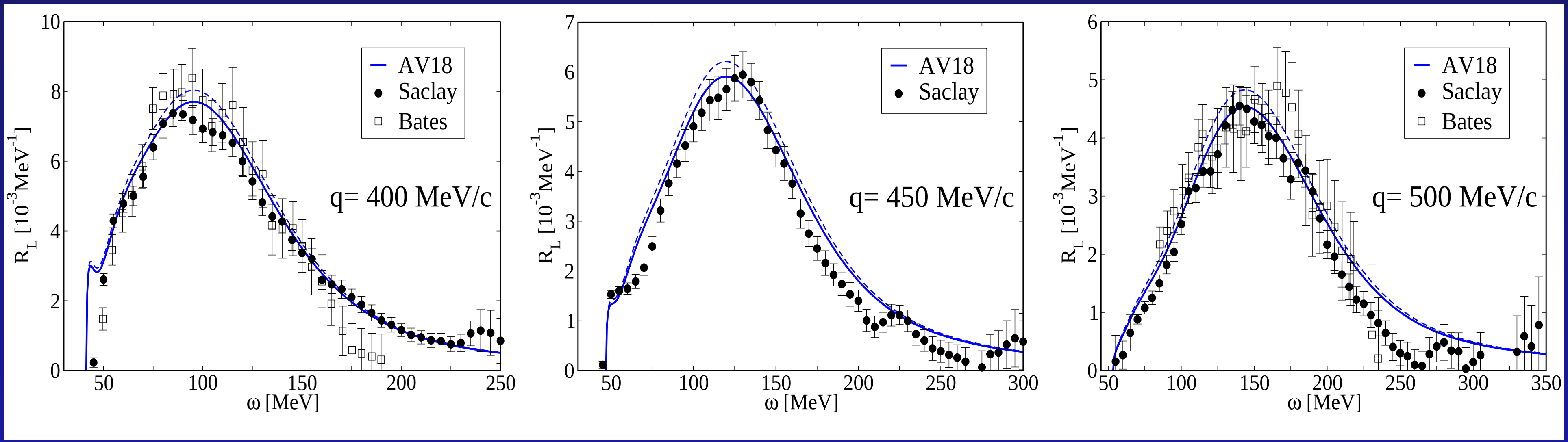


- With AV18 we find larger strength with respect to the experiment in the q.e. peak region.

Longitudinal Response Function:AV18

Comparison with experiment

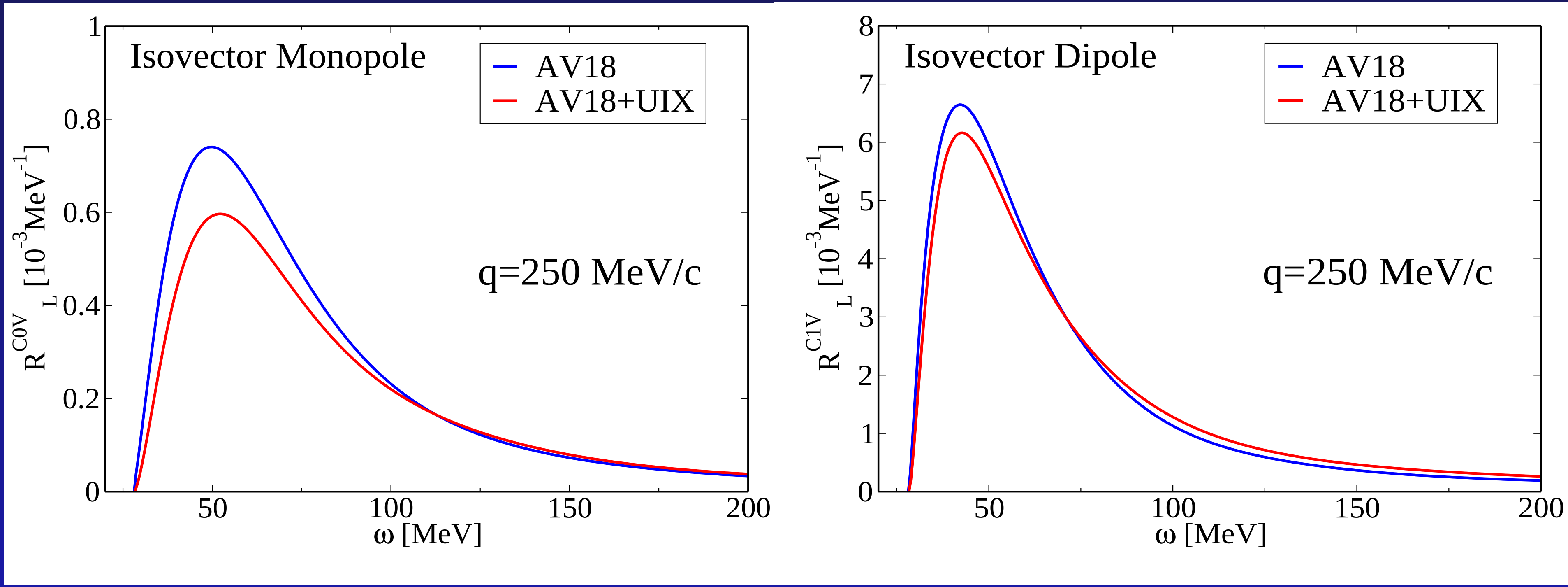
Medium-high momentum transfer: with relativistic form factors



- With AV18 we find larger strength with respect to the experiment in the q.e. peak region.
- Considering the effect of relativity in the nucleon form factor the agreement with experiment improves

Addition of 3NF

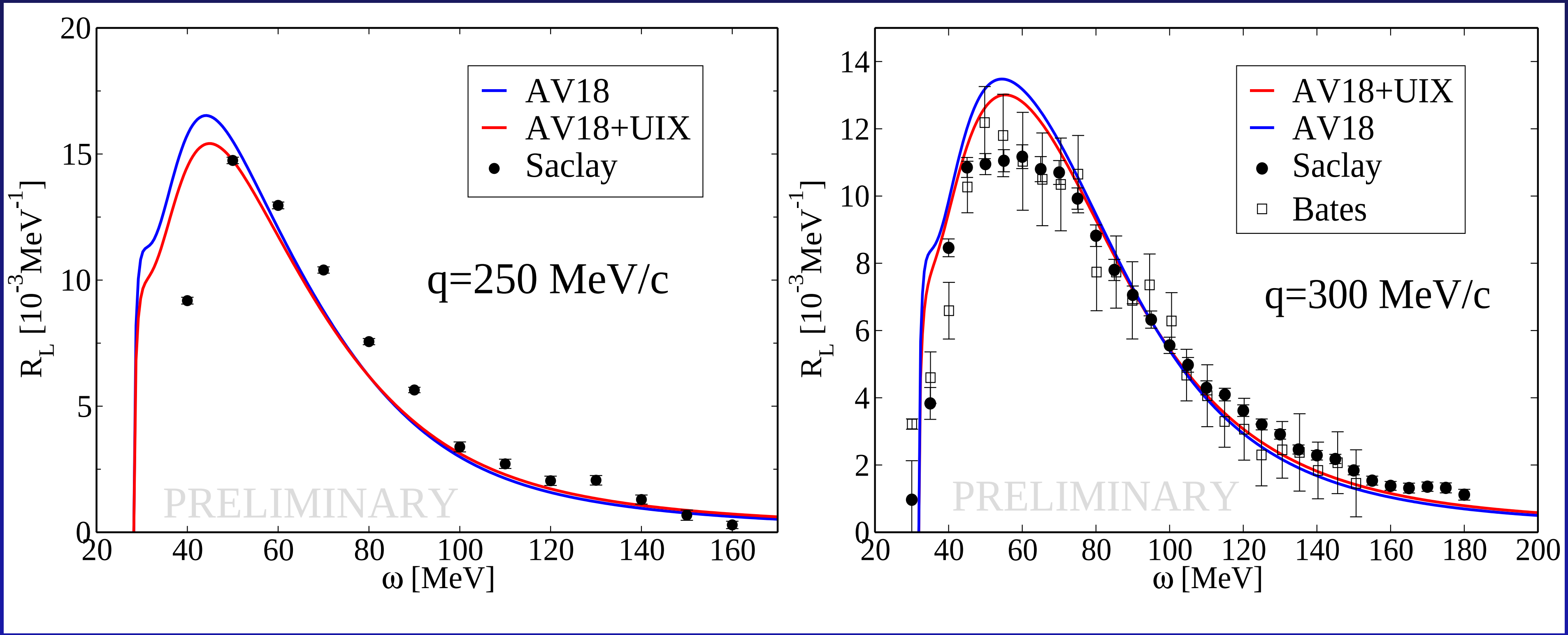
Isovector Monopole C_0^V and Dipole C_1^V responses



- The addition of UIX reduces the isovector monopole peak of 20%
- The addition of UIX reduces the isovector dipole peak of 7% and enhances the tail of 20-30% at pion-threshold (as for the photon!)

Longitudinal Response Function: AV18+UIX

Three-body force only in $C_0^{V/S}$ and C_1^V



- The preliminary addition of the UIX 3-body force improves the comparison with the experiment
- Larger effect of UIX is expected when including it in all multipoles.

Conclusion and Outlook

- We have presented a summary of the recent results obtained with the LIT and EIHH methods, which demonstrate the power of this approach.
- Exact calculations of photoabsorption reactions have renewed the experimental interest in the field!
  New measurement planned at MaxLab@Lund and TUNL.
- Investigation of electron scattering with realistic forces and consistent MEC can shed more light on our knowledge of 3NF and mesonic degrees of freedom
- Future: extend the "realistic" investigation of e.m. reactions to heavier system to investigate astrophysical reactions, like radiative capture ^{2}H$(\alpha,\gamma)^6$He, ^{3}H$(\alpha,\gamma)^7$Be, ^{7}Be$(p,\gamma)^8$B

Explicit Inclusion of MEC

- The MTI-III has the form

$$V = V_1(r) + V_2(r)\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 + V_3(r)\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + V_4(r)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$$

where $V(r) \propto J_m(r)$ with J_m scalar meson propagator and $r = |\mathbf{r}_1 - \mathbf{r}_2|$

Explicit Inclusion of MEC

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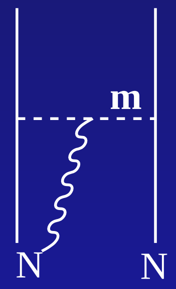
- The consistent MEC has only meson in flight terms



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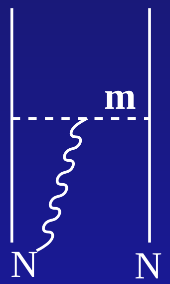

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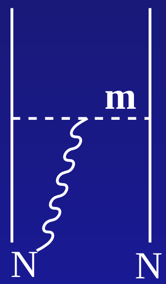

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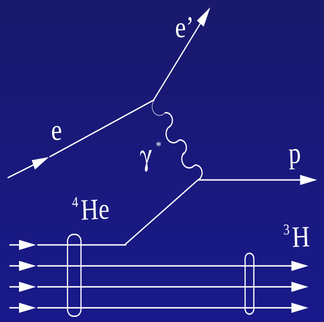

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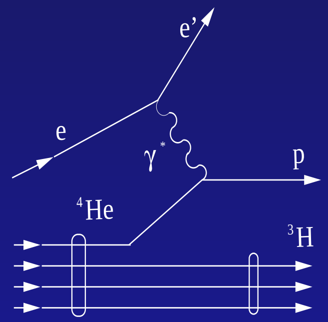

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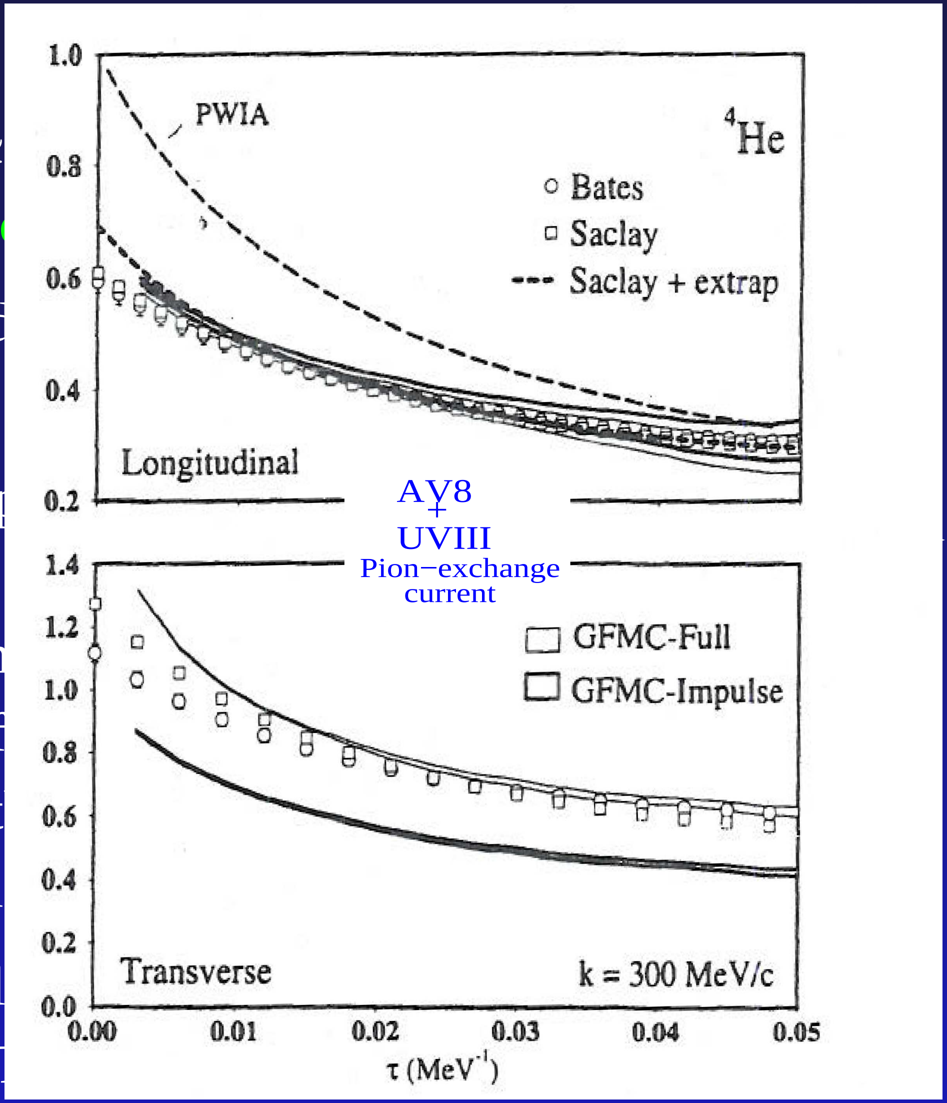

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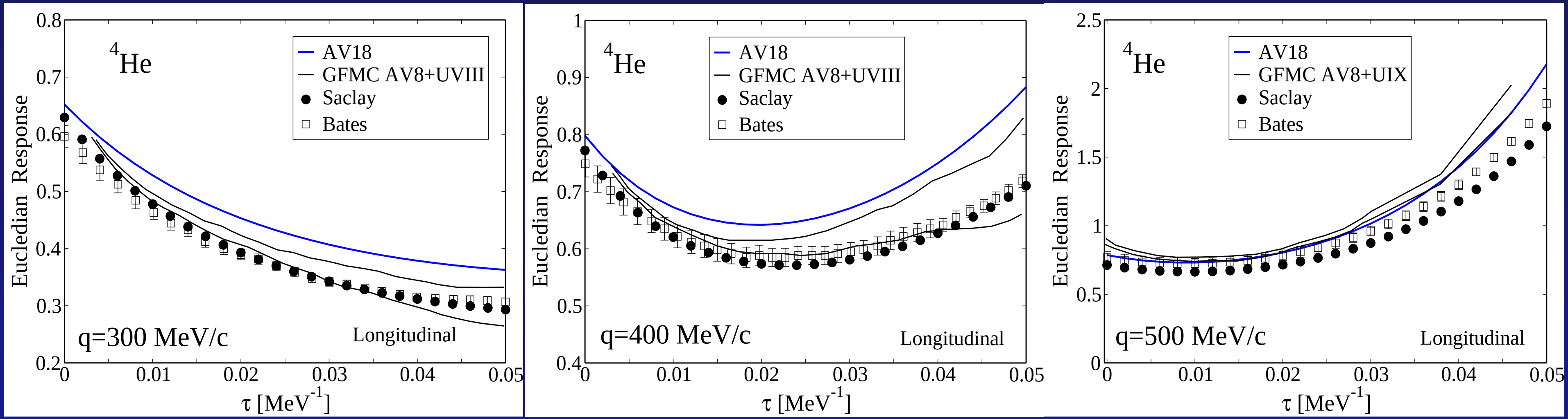
Longitudinal Response Function

Comparison with GFMC



GFMC from J. Carlson and R. Schiavilla, PRL **68**, 3682 (1992)
J. Carlson. J. Jourdan, R. Schiavilla and I. Sick, PRC **65**, 024002 (2002).

Estimate effect of 3NF ⇒ If the AV8 and AV18 lead to similar result, we expect 3NF to produce:

- "global" decrease of the total strength, with larger effect at low energy for $q = 300$ and 400 MeV/c
- only at tiny effect $q = 500$ MeV/c.

Transverse Response Function

One-body current

Spin Current $\mathbf{J}_1^s \sim \frac{i}{2m} \sum_k (\boldsymbol{\sigma}_k \times \mathbf{q}) e^{i\mathbf{q}\mathbf{r}_k}$

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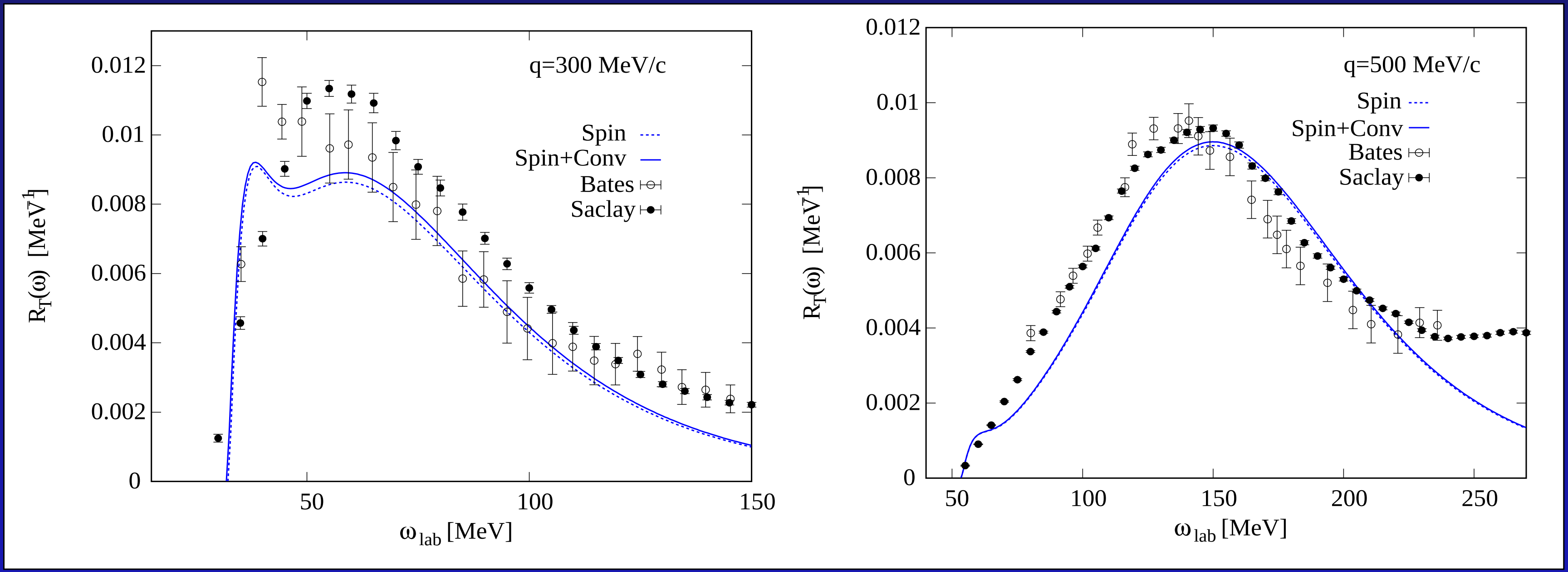

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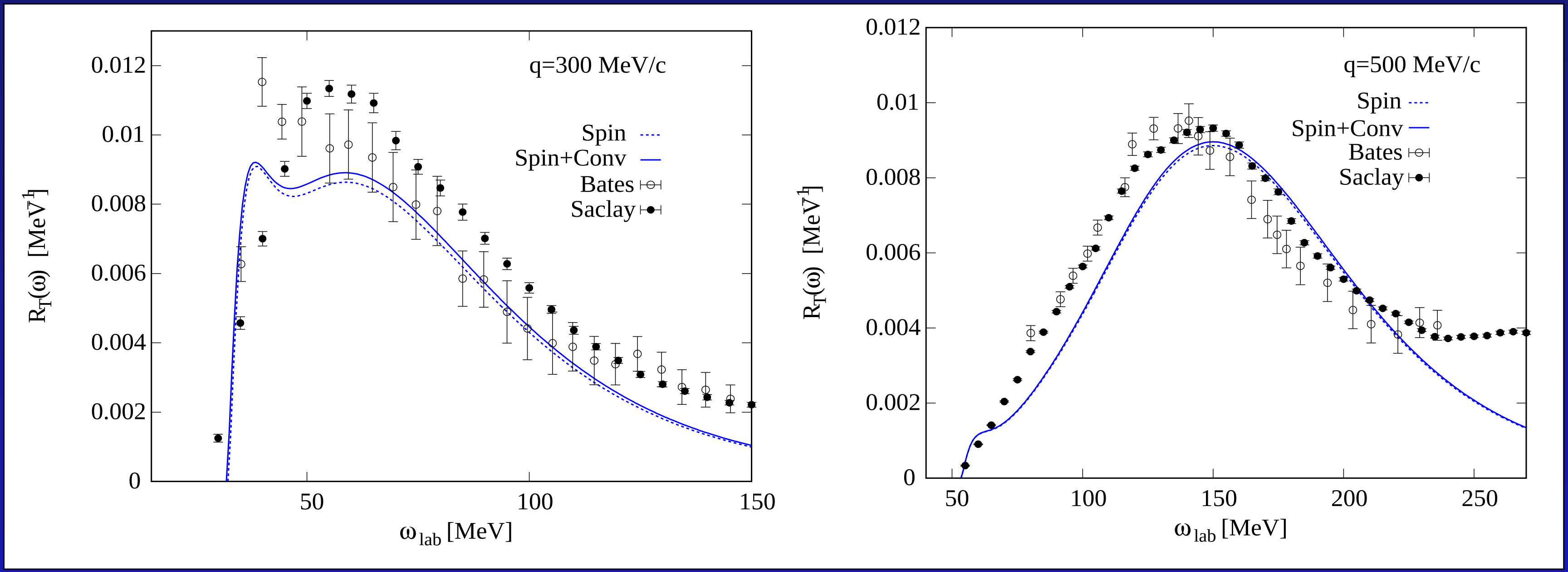
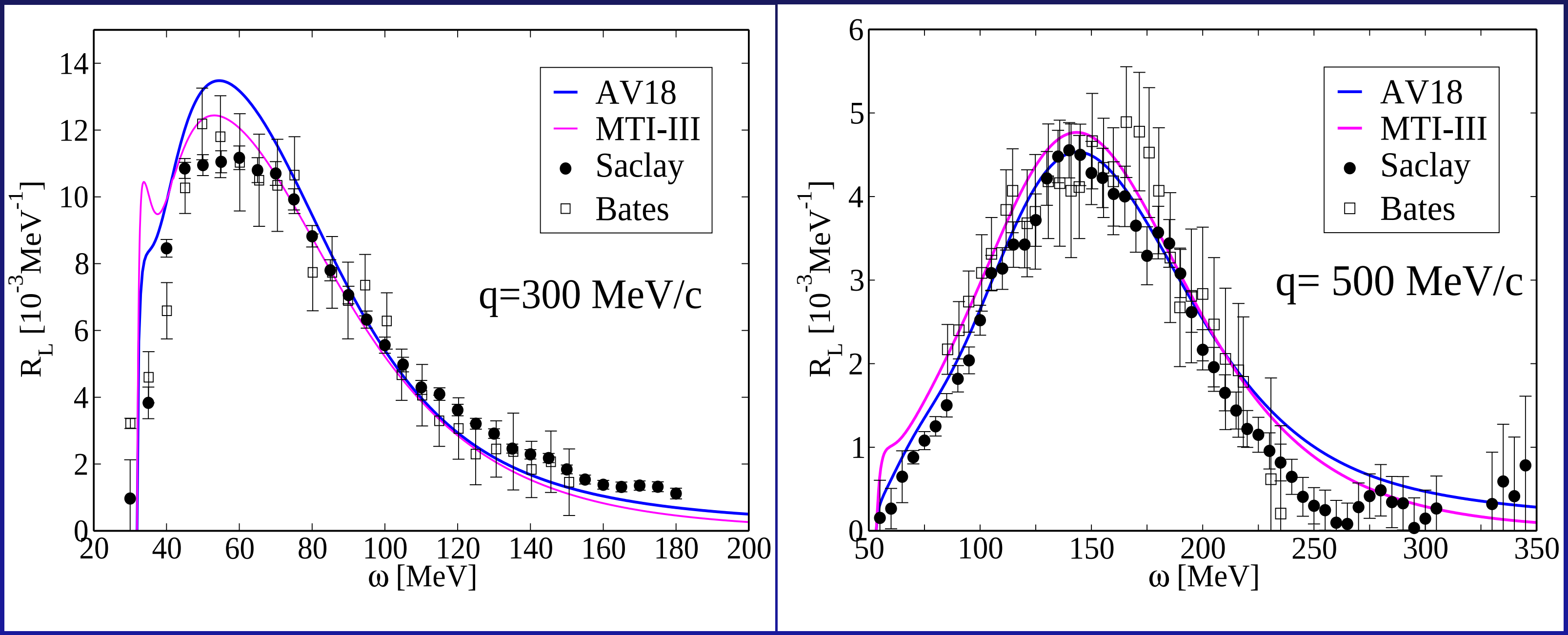


Is the missing strength due to the two-body current?

Longitudinal Response Function

Comparison of Realistic/Semirealistic Interaction



MTI-III from S.B., H.Arenhövel, N. Barnea, W. Leidemann, G. Orlandini, PRC **76**, 014003 (2007)

- In the q.e. peak with the AV18 we find larger strength for $q = 300$ MeV/c and less for $q = 500$ MeV/c with respect to the MTI-III.
- C_1^V behaves like for photoabsorption, but in ee' other multipoles are involved
- R_L at $q = 500$ MeV/c may not yet be fully converged in J.