Electromagnetic observables from coupled-cluster theory

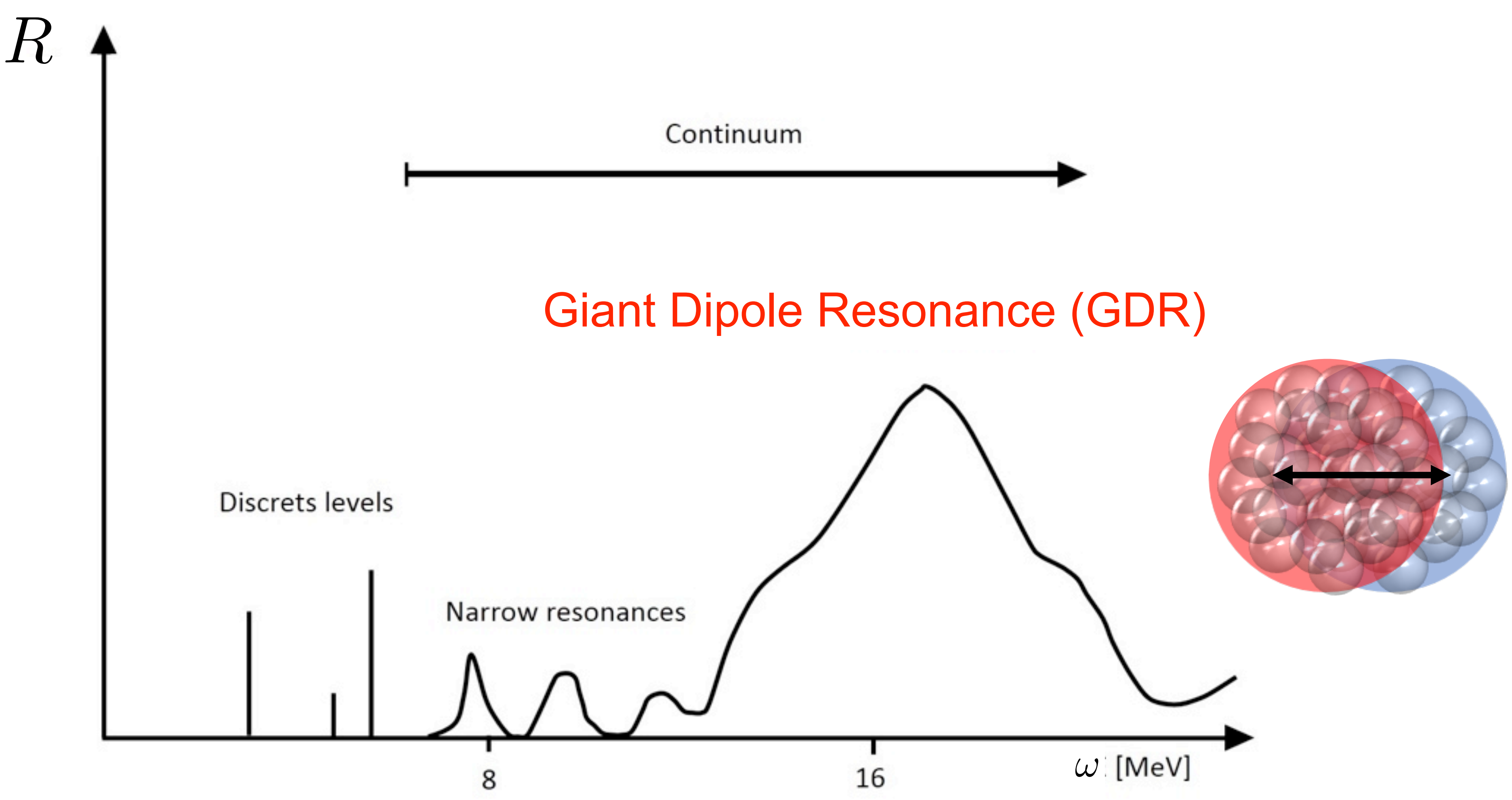
Sonia Bacca

Johannes Gutenberg Universität Mainz and TRIUMF

March 1st, 2018

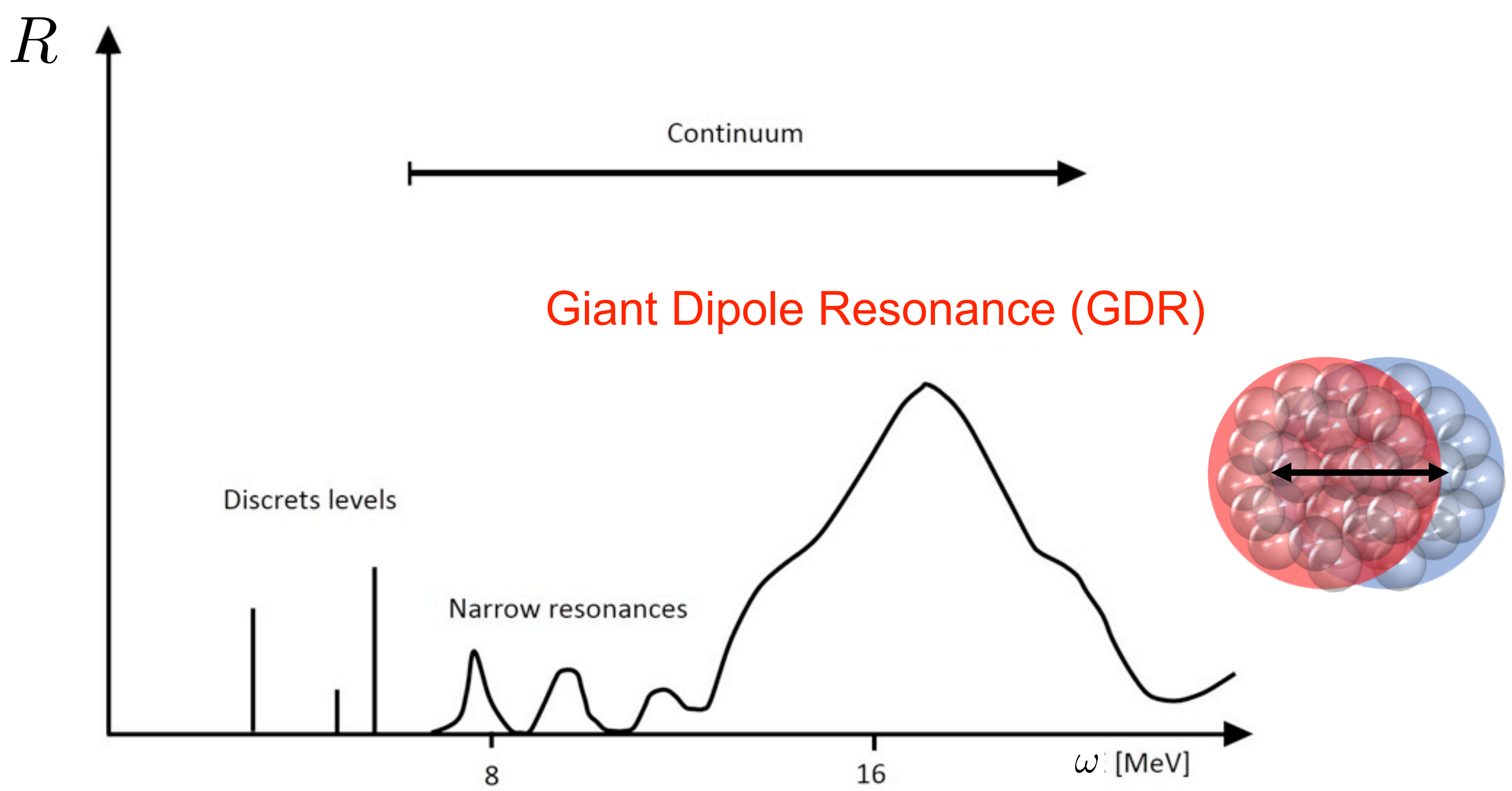
Strength functions

Example: dipole strength function



Strength functions

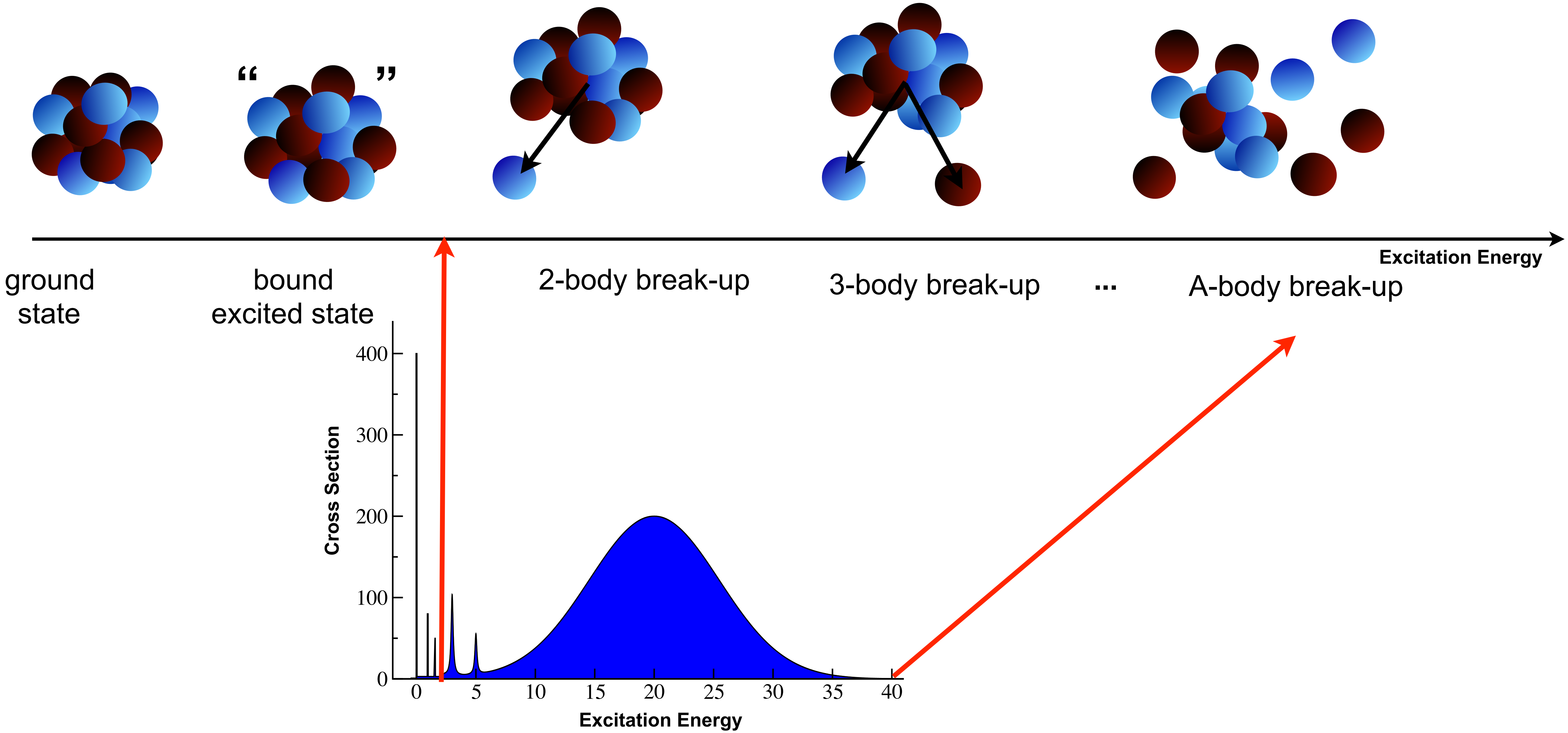
Example: dipole strength function



Continuum problem

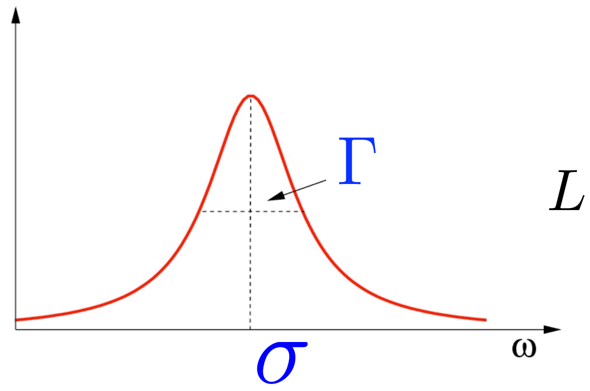
$$R(\omega) = \sum\!\!\!\!\!\!\int_f \left| \left\langle \psi_f \middle| \Theta \middle| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$$

Depending on E_f, many channels may be involved



LIT Lorentz Integral Transform

A method that allows to circumvent the continuum problem by reducing it to the solution of a bound-state-like equation



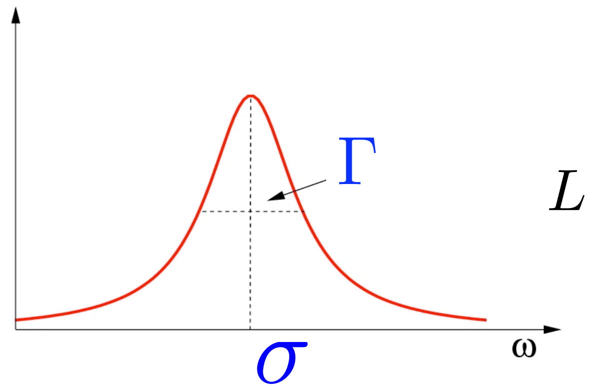
$$L(\sigma,\Gamma) = \frac{\Gamma}{\pi}\int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2}$$

$$(H - E_0 - \sigma + i\Gamma) \mid \tilde{\psi}\rangle = \Theta \mid \psi_0\rangle$$

How do we address it?

LIT Lorentz Integral Transform

A method that allows to circumvent the continuum problem by reducing it to the solution of a bound-state-like equation



$$L(\sigma,\Gamma) = \frac{\Gamma}{\pi}\int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2}$$

$$(H - E_0 - \sigma + i\Gamma)\,|\,\tilde{\psi}\rangle = \Theta\,|\,\psi_0\rangle$$

+

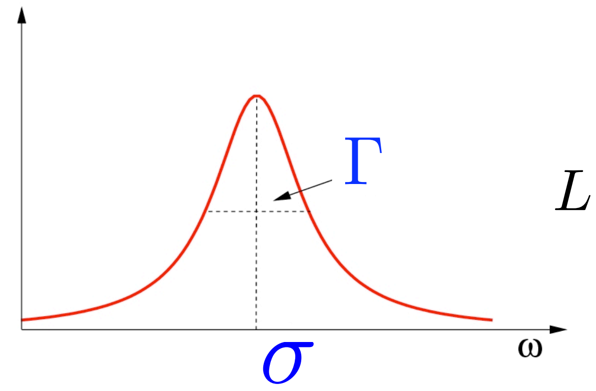
CC Coupled-cluster theory

Accurate many-body theory with mild polynomial scaling in mass number

How do we address it?

LIT Lorentz Integral Transform

A method that allows to circumvent the continuum problem by reducing it to the solution of a bound-state-like equation



$$L(\sigma,\Gamma) = \frac{\Gamma}{\pi}\int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2}$$

$$(H - E_0 - \sigma + i\Gamma) \,|\, \tilde{\psi}\rangle = \Theta \,|\, \psi_0\rangle$$

+

CC Coupled-cluster theory

Accurate many-body theory with mild polynomial scaling in mass number

=

LIT-CC

An approach to many-body break-up induced reactions with a proper accounting of the continuum

Photonuclear reactions

S.B. *et al.*, Phys. Rev. Lett. **111**, 122502 (2013)

$$(\bar{H} - E_0 - \sigma + i\Gamma)|\tilde{\Psi}_R\rangle = \bar{\Theta}|\Phi_0\rangle$$

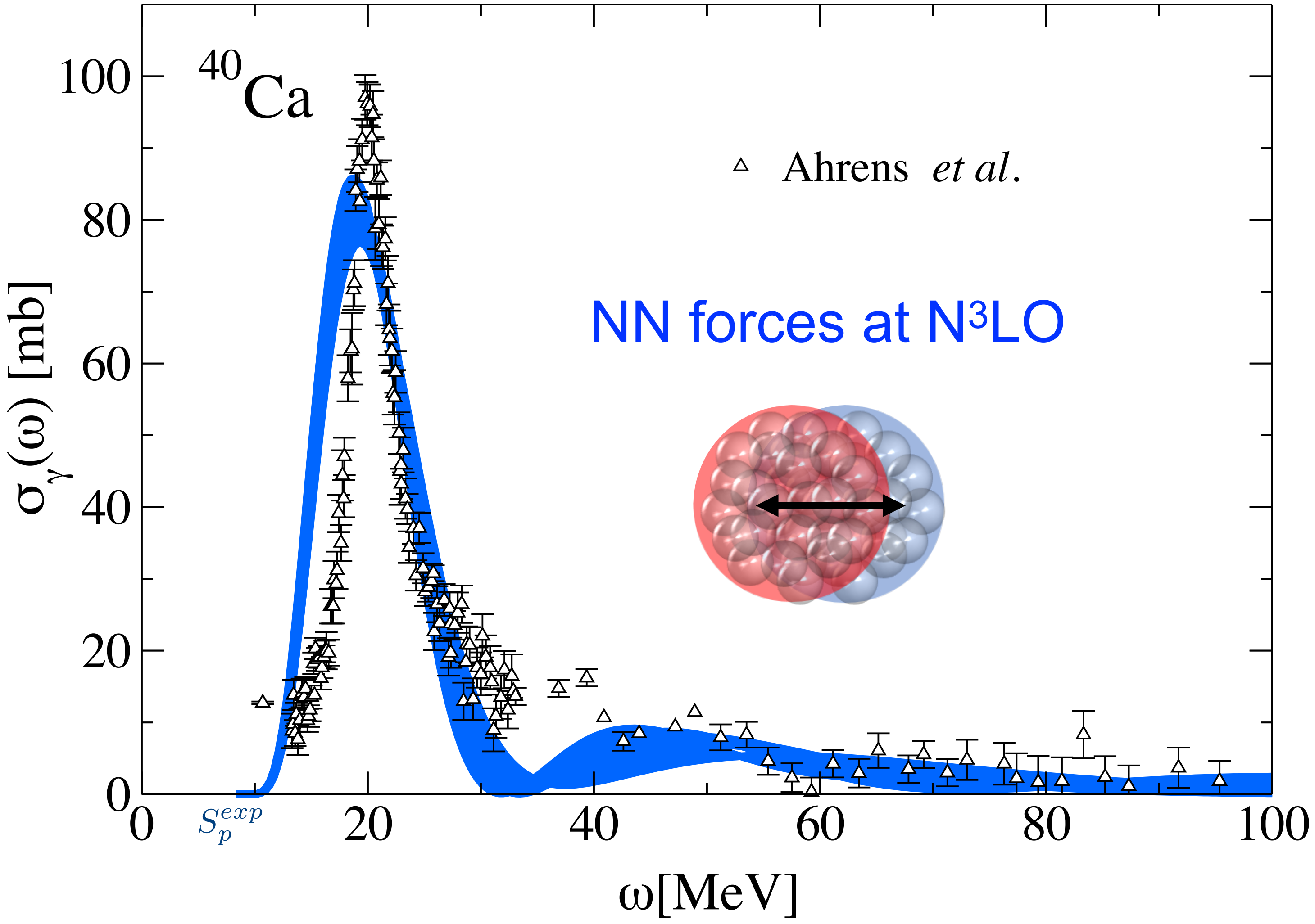
$$\bar{H} = e^{-T} H e^{T}$$

$$\bar{\Theta} = e^{-T} \Theta e^{T}$$

$$|\tilde{\Psi}_R\rangle = \hat{R}|\Phi_0\rangle$$

Implementation at the singles and doubles level

S.B. *et al.*, Phys. Rev. C **90**, 064619 (2014)



Sum rules

$$m_n = \int_0^\infty d\omega \; \omega^n R(\omega) = \langle \Psi_0 | \hat{\Theta}^\dagger (\hat{H} - E_0)^n \hat{\Theta} | \Psi_0 \rangle$$

Sum rules

$$m_n = \int_0^\infty d\omega\ \omega^n R(\omega) = \langle \Psi_0 | \hat{\Theta}^\dagger (\hat{H} - E_0)^n \hat{\Theta} | \Psi_0 \rangle$$

Bremsstrahlung sum rule $$m_0 = \langle \Phi_0 | (1+\Lambda) \overline{\Theta}_N^\dagger \cdot \overline{\Theta}_N | \Phi_0 \rangle$$

Polarizability sum rule $$\alpha_D = 2\alpha m_{-1} = 2\alpha \lim_{\Gamma \to 0} \langle \Phi_0 | (1+\Lambda) \overline{\Theta}_N^\dagger \frac{1}{\overline{H} - E_0 - i\Gamma} \overline{\Theta}_N | \Phi_0 \rangle$$

Sum rules

$$m_n = \int_0^\infty d\omega \; \omega^n R(\omega) = \langle \Psi_0 | \hat{\Theta}^\dagger (\hat{H} - E_0)^n \hat{\Theta} | \Psi_0 \rangle$$

Bremsstrahlung sum rule $\quad m_0 = \langle \Phi_0 | (1+\Lambda) \overline{\Theta}_N^\dagger \cdot \overline{\Theta}_N | \Phi_0 \rangle$

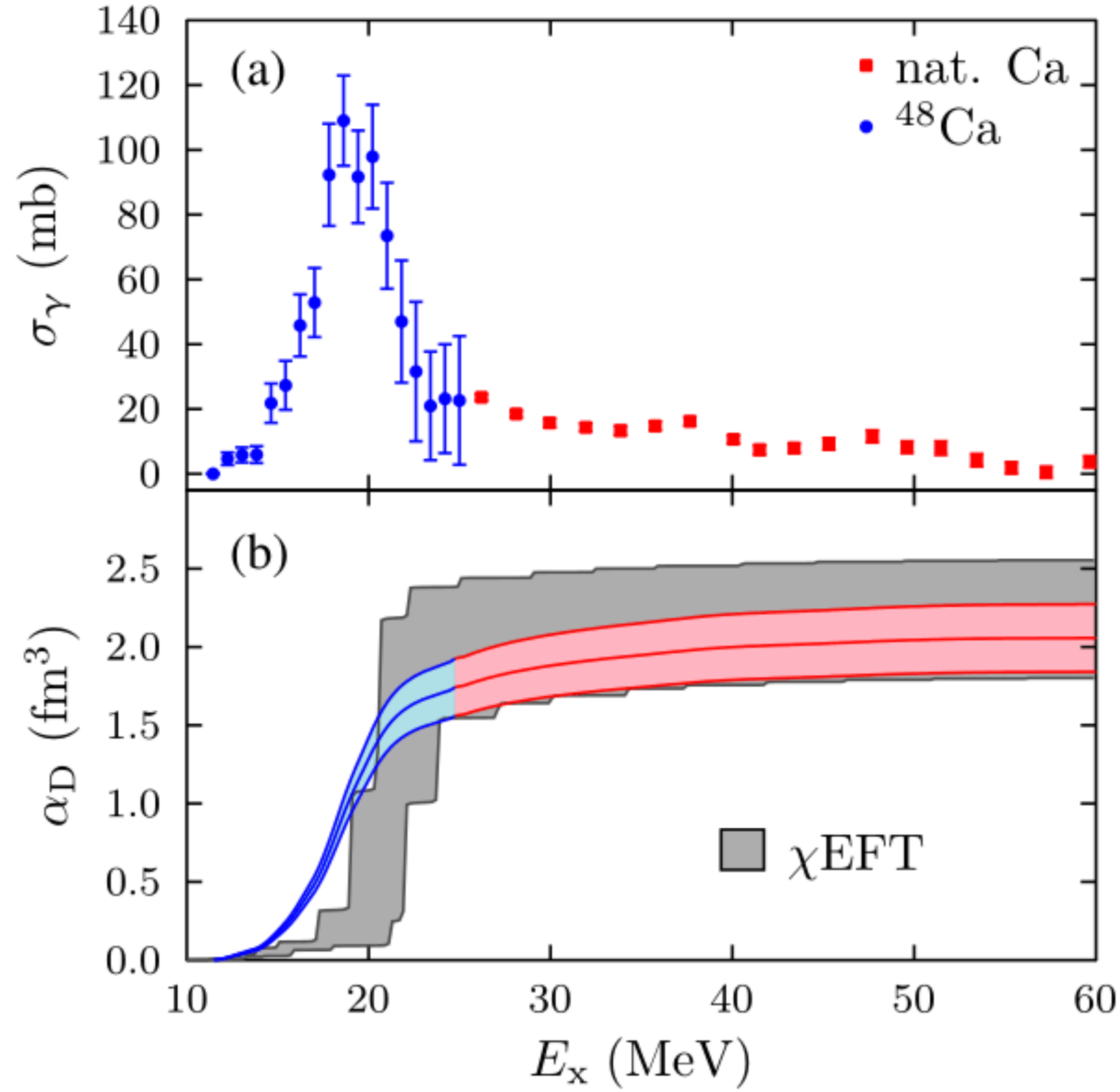
Polarizability sum rule $\quad \alpha_D = 2\alpha m_{-1} = 2\alpha \lim_{\Gamma \to 0} \langle \Phi_0 | (1+\Lambda) \overline{\Theta}_N^\dagger \frac{1}{\overline{H} - E_0 - i\Gamma} \overline{\Theta}_N | \Phi_0 \rangle$

Coupled cluster expansions $\quad T, \Lambda \quad$ ground-state ⇨ affecting $\bar{\Theta}_N$

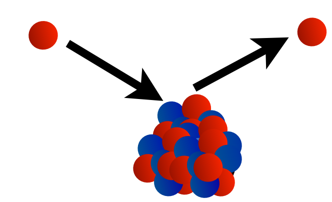
$R, L \quad$ excited-states (EoM)

Running sum rule

J.Birkhan, *et al.*, Phys. Rev. Lett. **118,** 252501 (2017)



Data by the Osaka-Darmstadt collaboration from (p,p')



Adding triples

Full triples are prohibitive

We will use linearized triples for ground state and EoM $T_3 = f(T_1, T_2)$

Adding triples

Full triples are prohibitive

We will use linearized triples for ground state and EoM $T_3 = f(T_1, T_2)$

Similarity transformed operator

M. Miorelli, PhD Thesis (2017)
M. Miorelli *et al.,* in preparation (2018)

$$\begin{aligned}\bar{\Theta}_N = \left[\Theta_N e^{T_1+T_2+T_3}\right]_C &= \bar{\Theta}_N^D + \left[\Theta_N\left(\frac{T_2^2}{2} + T_3 + T_1 T_3\right)\right]_C \\ &\simeq \bar{\Theta}_N^D + \left[\Theta_N\left(\frac{T_2^2}{2}\right)\right]_C \\ &\simeq \bar{\Theta}_N^D\end{aligned}$$

Adding triples

Full triples are prohibitive

We will use linearized triples for ground state and EoM $T_3 = f(T_1, T_2)$

Similarity transformed operator

M. Miorelli, PhD Thesis (2017)
M. Miorelli *et al.,* in preparation (2018)

$$\bar{\Theta}_N = \left[\Theta_N e^{T_1+T_2+T_3}\right]_C = \bar{\Theta}_N^D + \left[\Theta_N \left(\frac{T_2^2}{2} + T_3 + T_1 T_3\right)\right]_C$$
$$\simeq \bar{\Theta}_N^D + \left[\Theta_N \left(\frac{T_2^2}{2}\right)\right]_C$$
$$\simeq \bar{\Theta}_N^D$$

^{4}He	^{16}O
m_0[fm]	
0.951	4.87
0.950	4.92
0.949	4.90

Adding triples

Full triples are prohibitive

We will use linearized triples for ground state and EoM $T_3 = f(T_1, T_2)$

Similarity transformed operator

M. Miorelli, PhD Thesis (2017)
M. Miorelli *et al.*, in preparation (2018)

$$\bar{\Theta}_N = \left[\Theta_N e^{T_1+T_2+T_3}\right]_C = \bar{\Theta}_N^D + \left[\Theta_N \left(\frac{T_2^2}{2} + T_3 + T_1 T_3\right)\right]_C$$

$$\simeq \bar{\Theta}_N^D + \left[\Theta_N \left(\frac{T_2^2}{2}\right)\right]_C$$

$$\simeq \bar{\Theta}_N^D$$

^{4}He	^{16}O
m_0[fm]	
0.951	4.87
0.950	4.92
0.949	4.90

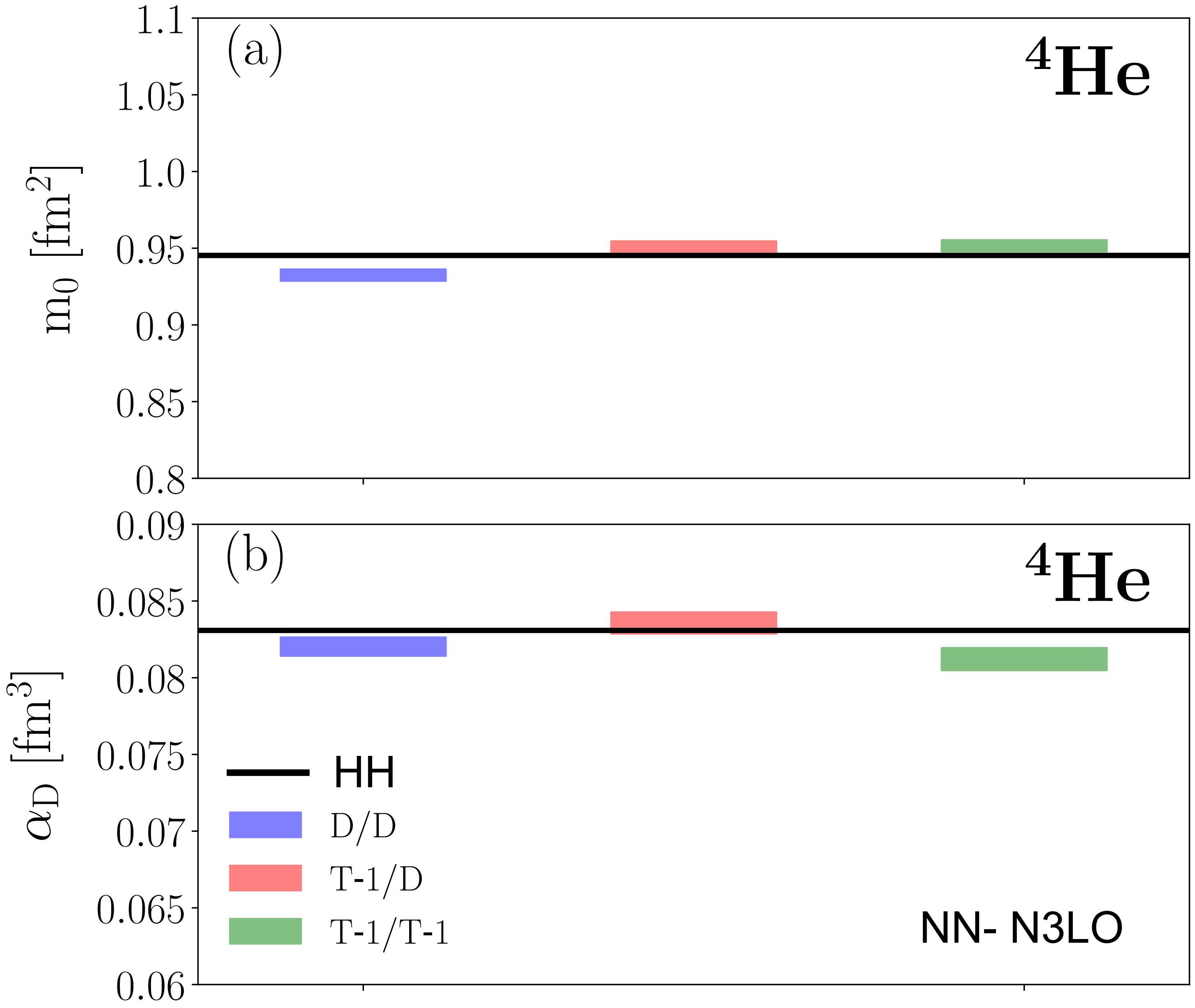
By using only $\bar{\Theta}_N^D$ you are missing 0.2 - 0.6% of the strength only

Much simpler and the only feasible calculation in heavy nuclei

Benchmark

M. Miorelli *et al.*, in preparation (2018)

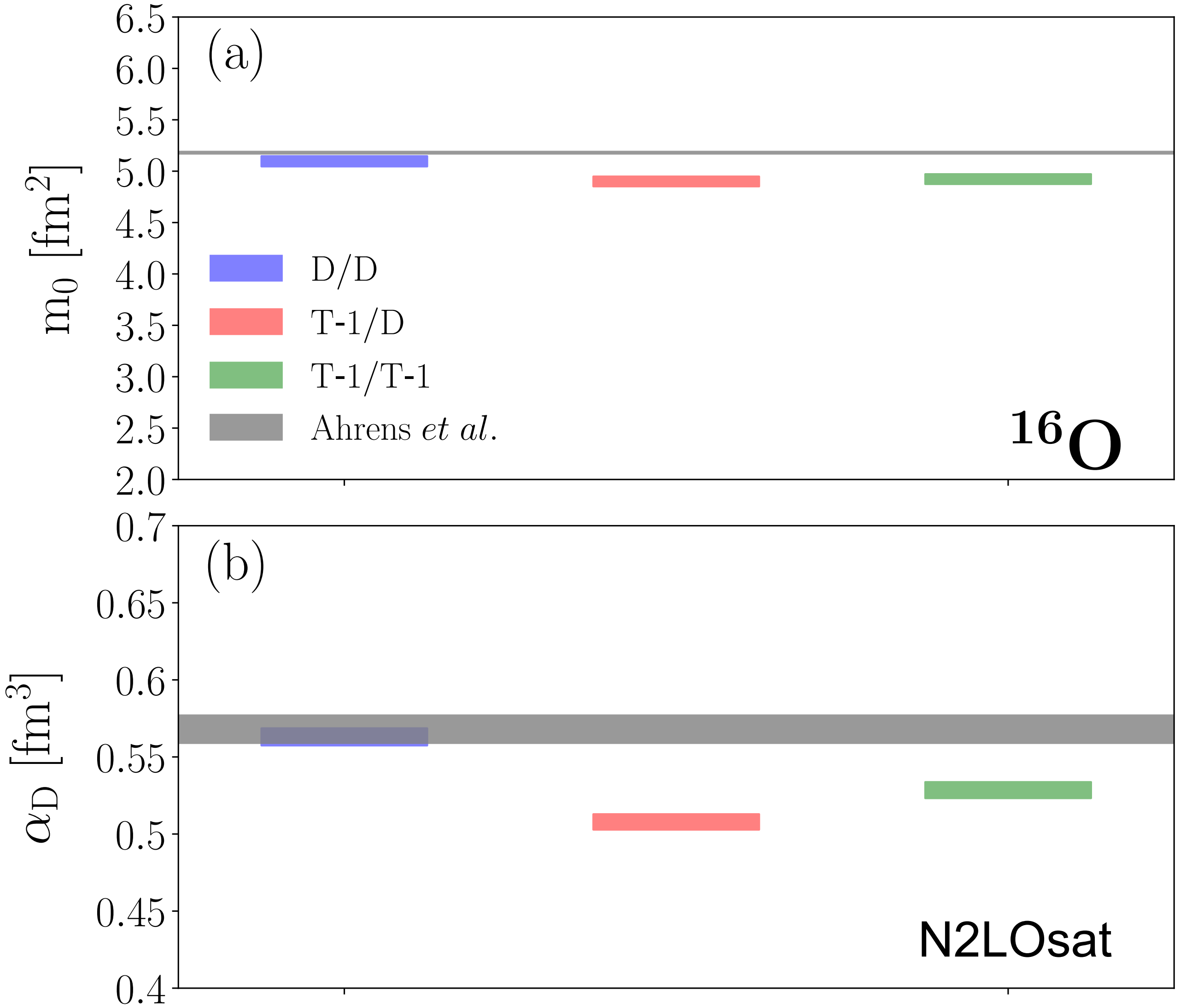
Hyperspherical harmonics (HH) contain all correlations (up to quadruples)



Comparison with experiment and theory

M. Miorelli *et al.*, in preparation (2018)

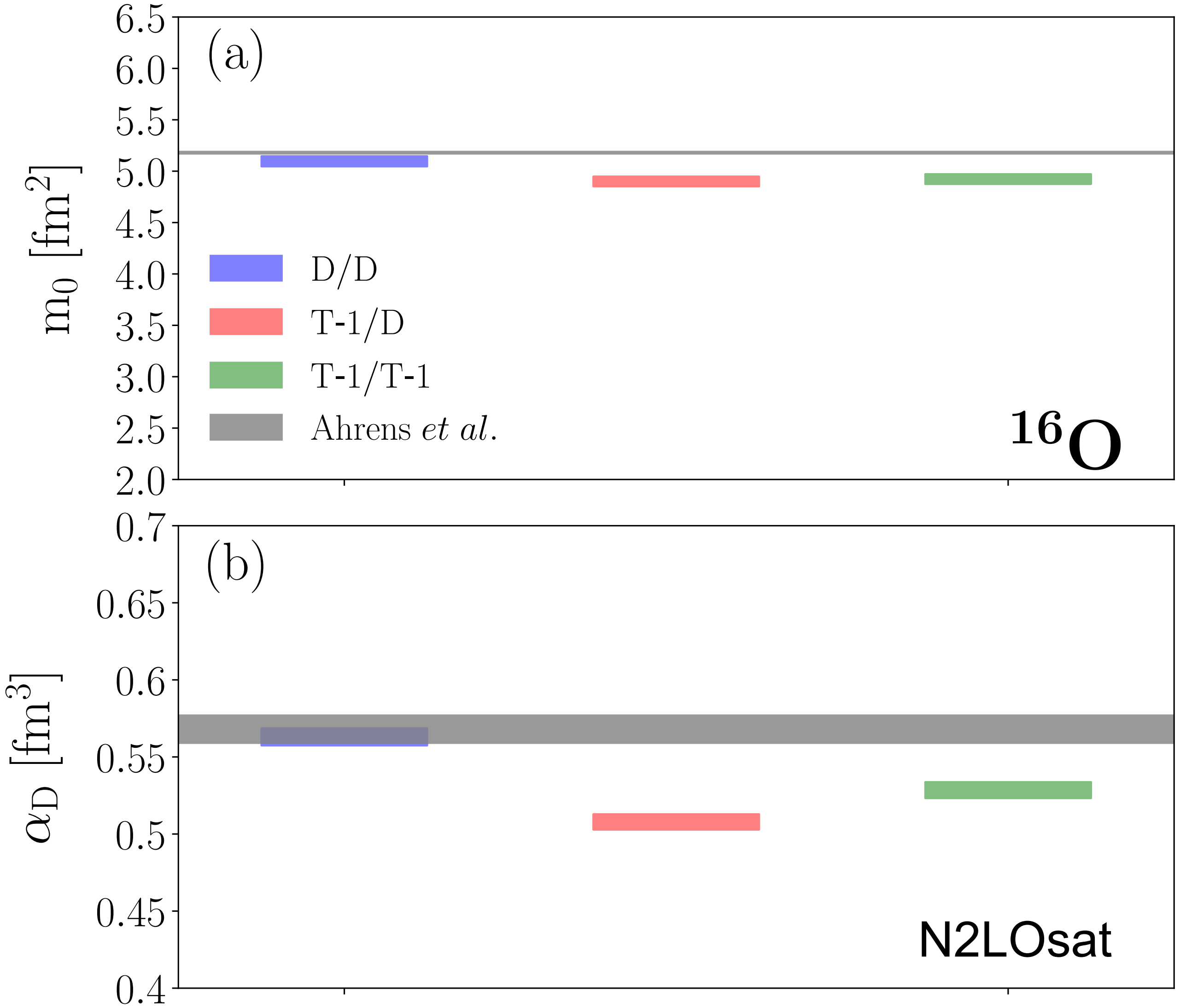
Experimental data from photoabsorption cross sections

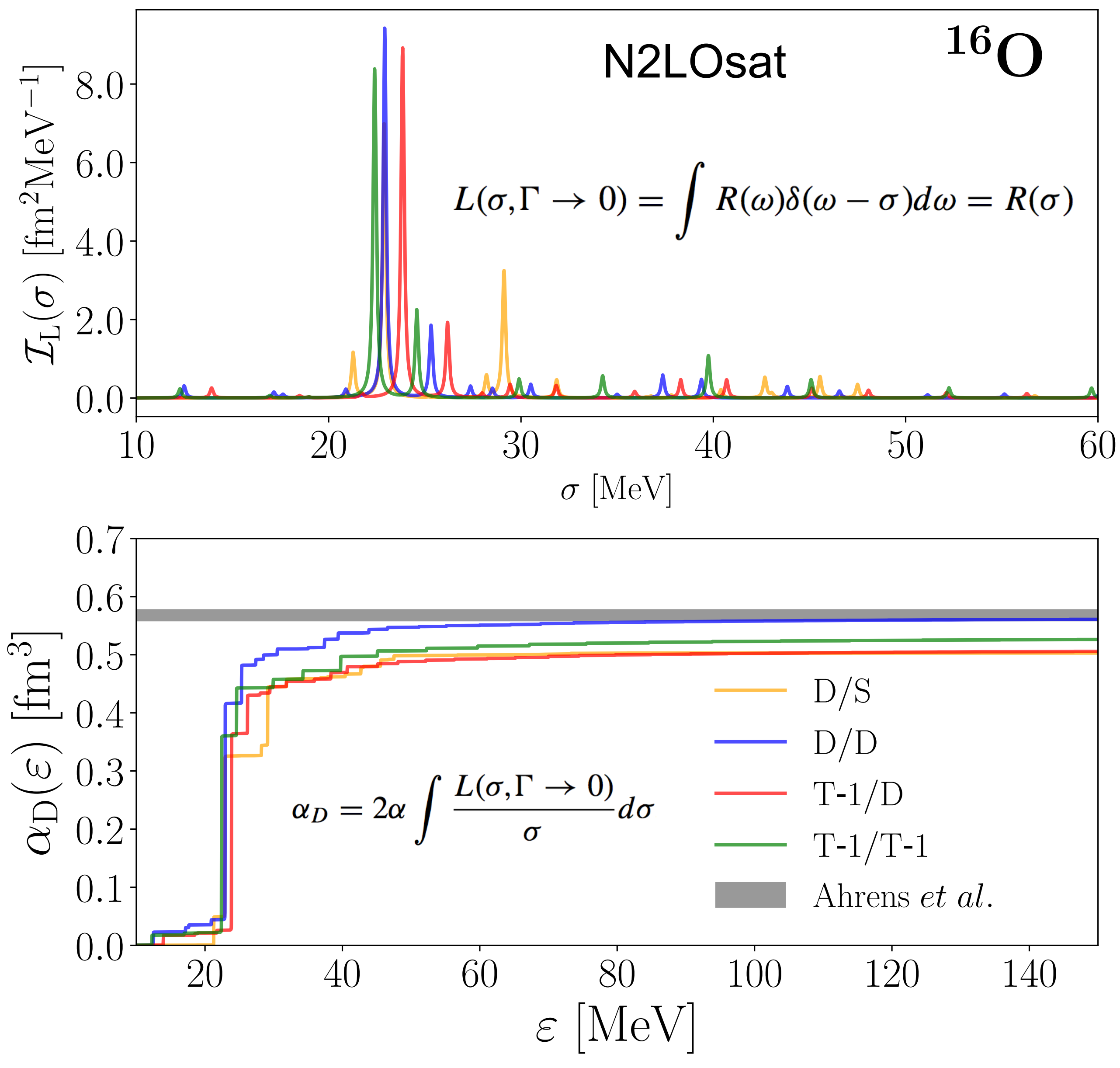


Comparison with experiment and theory

M. Miorelli *et al.*, in preparation (2018)

Experimental data from photoabsorption cross sections

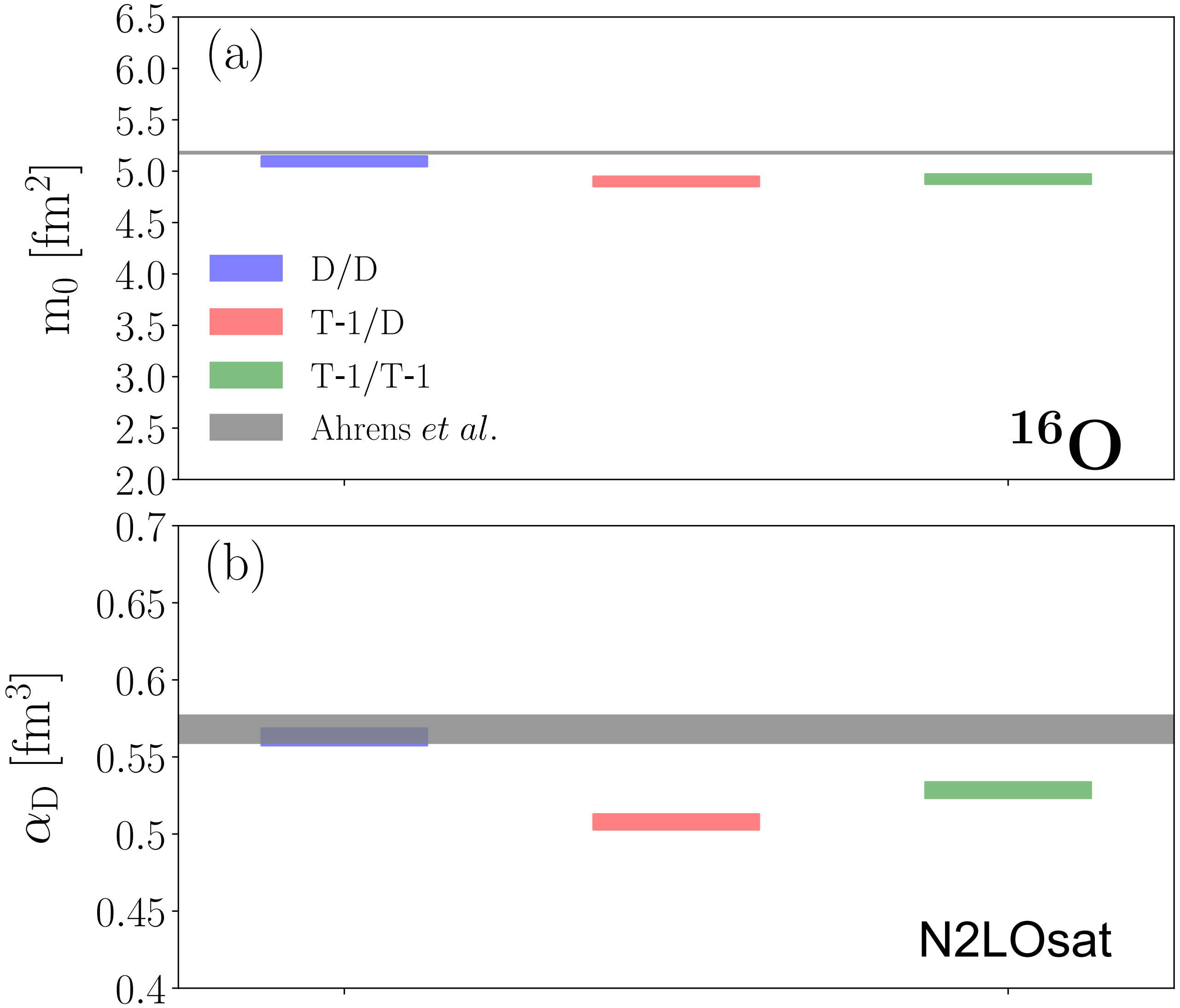


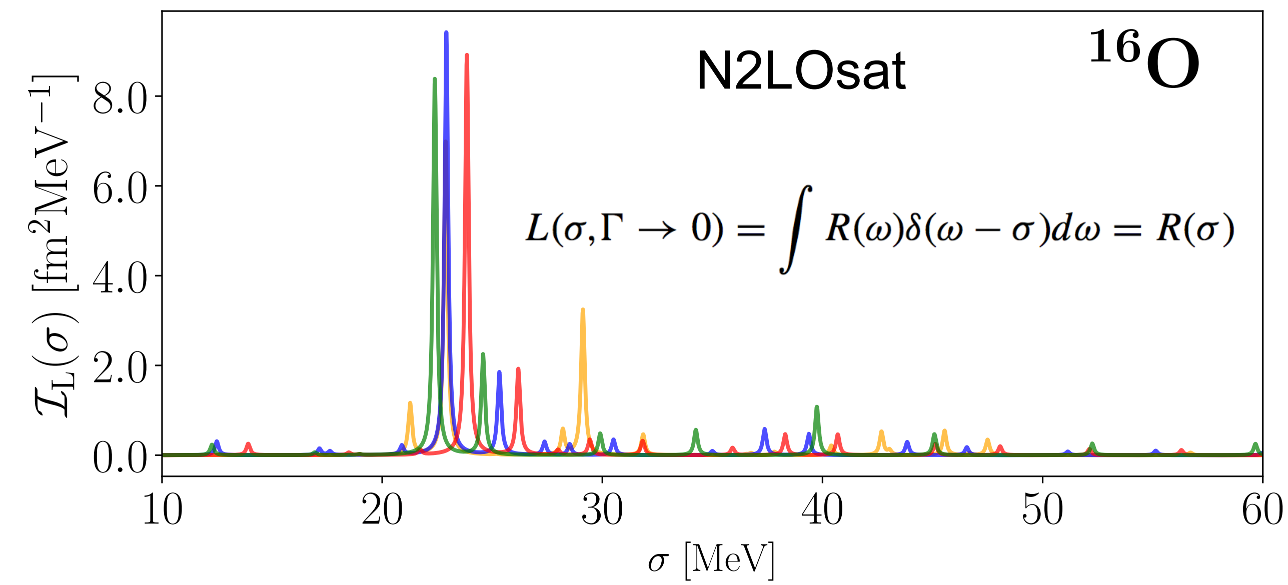


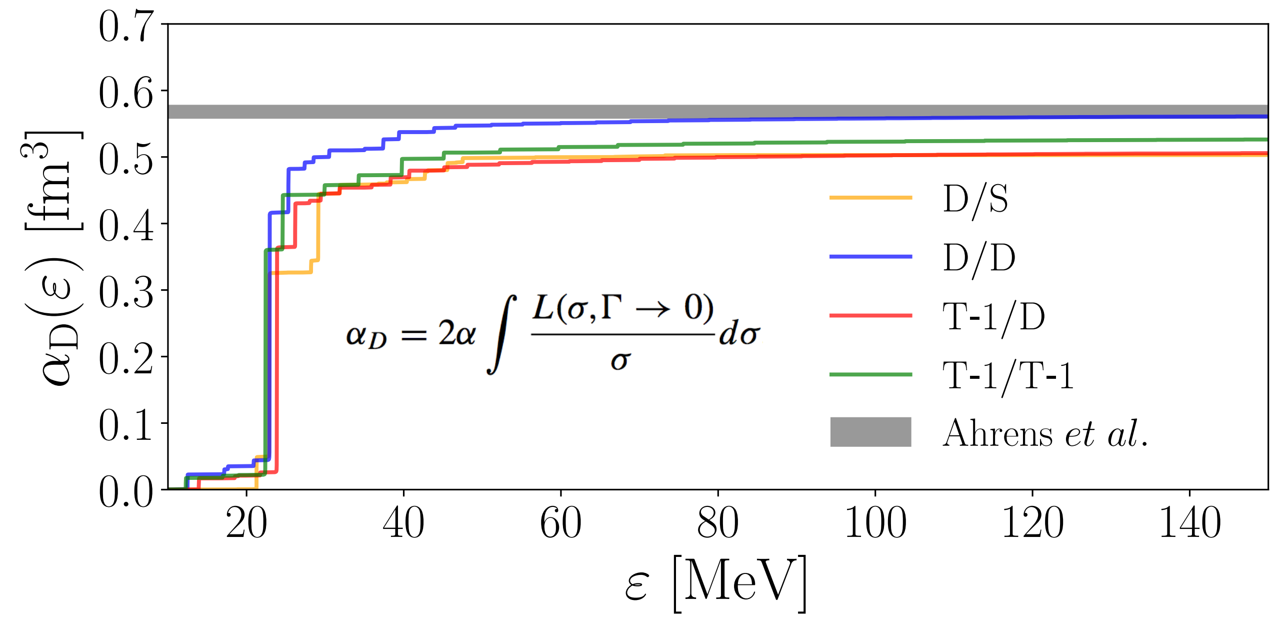
Comparison with experiment and theory

M. Miorelli *et al.*, in preparation (2018)

Experimental data from photoabsorption cross sections





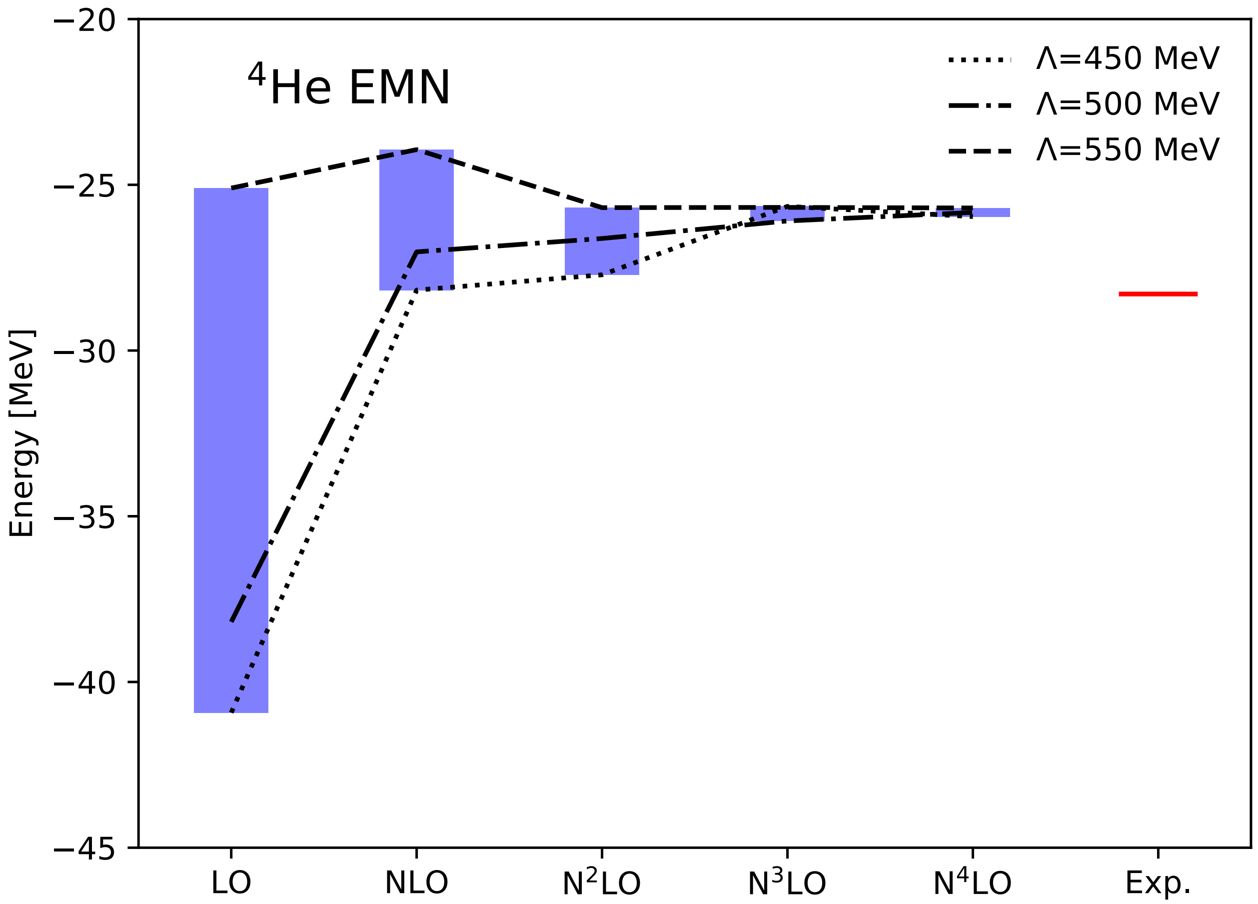


Barbieri et al., arXiv:1711.04698 SCGF approach obtains 0.50 fm^3 comparable to D/S giving 0.502 fm^3

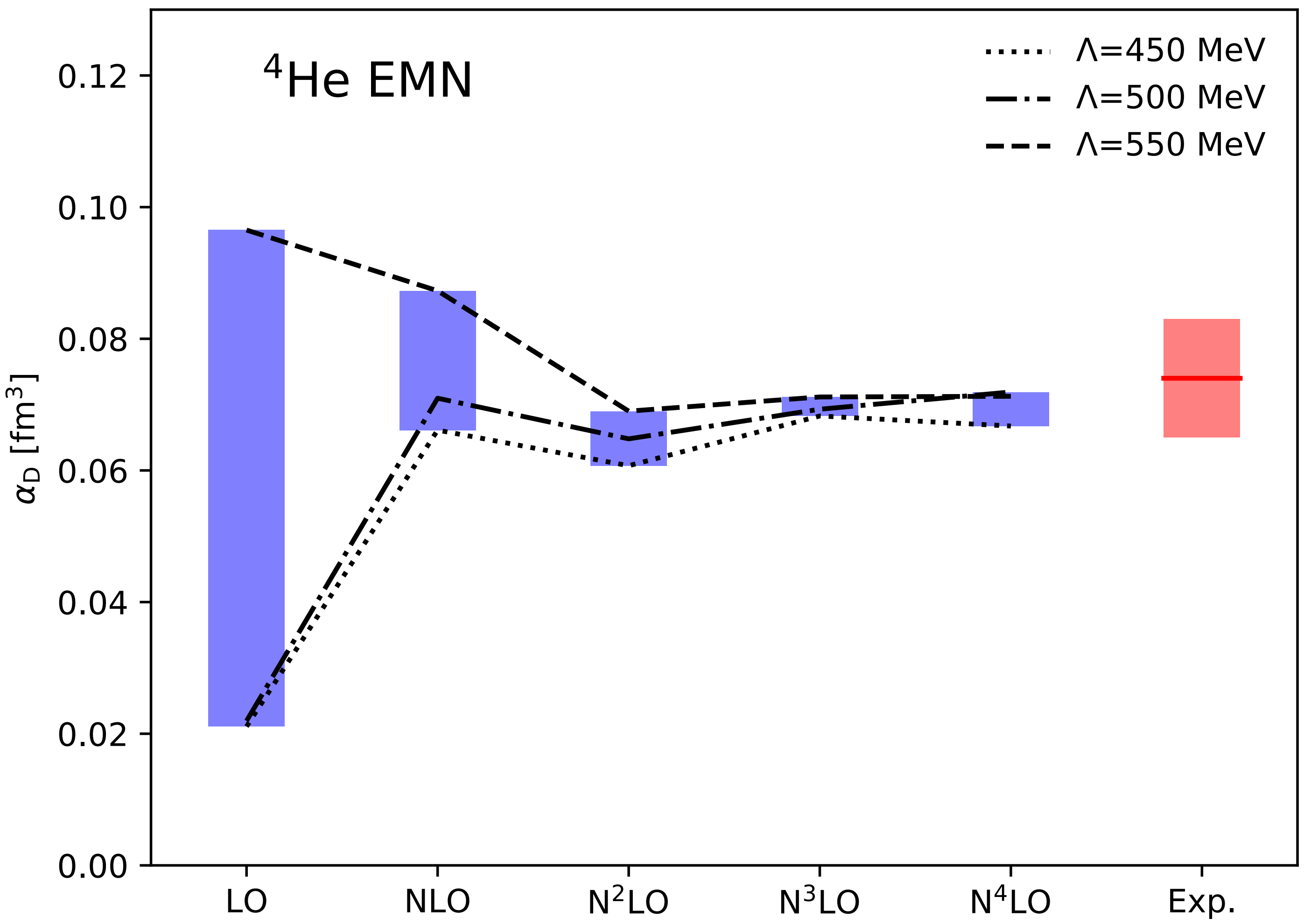
Chiral convergence

J. Simonis et al. (2018)

EMN: Entem, Machleidt and Nosyk, PRC 96, 024004(2017)



D/D calculation
Final Goal: T-1/D with three-body forces

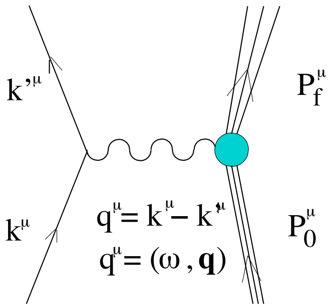


This will help shed light on systematic uncertainties in muonic ^{4}He (see talks by Hernandez and Nevo Dinur)

Coulomb sum rule

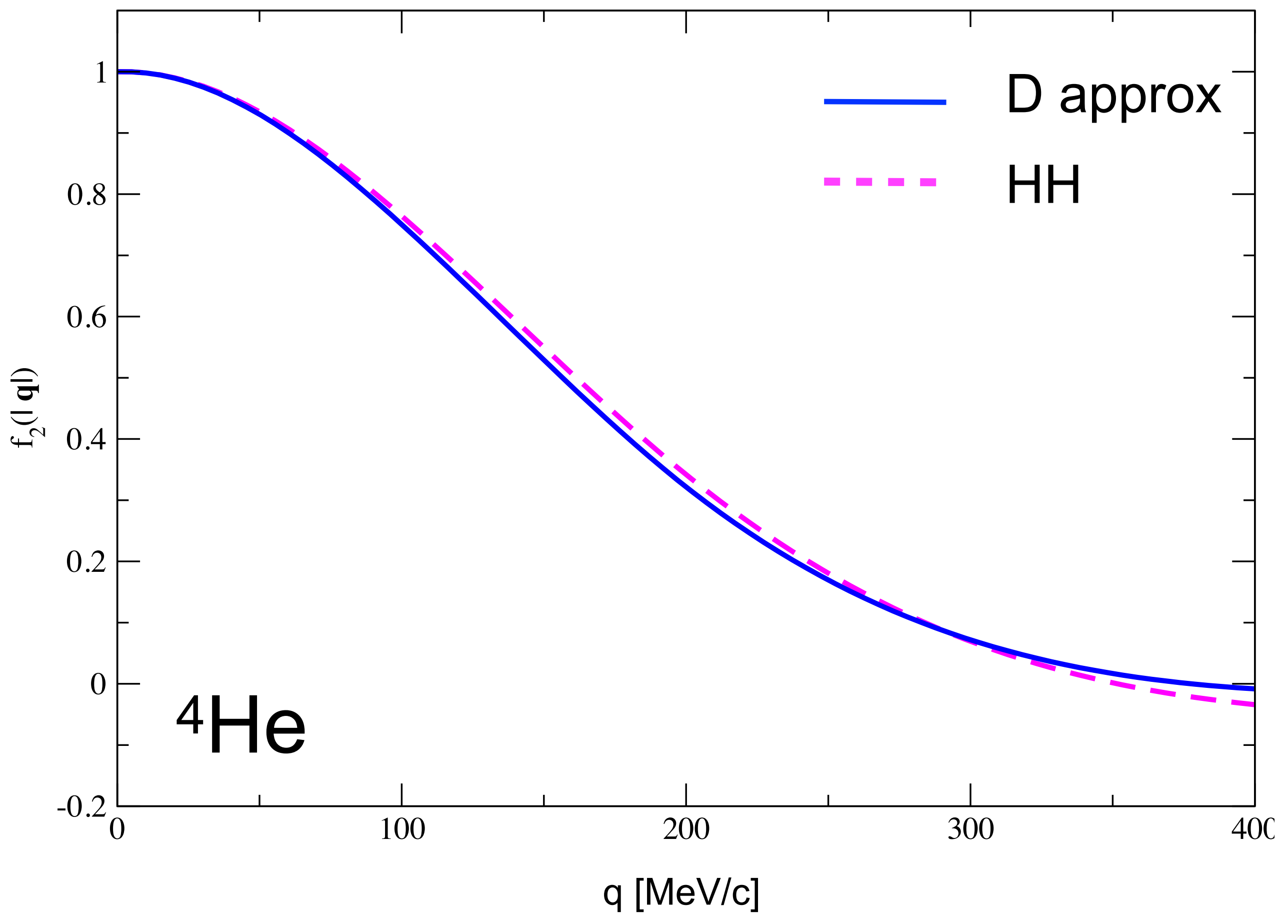
Total strength of inelastic longitudinal response function

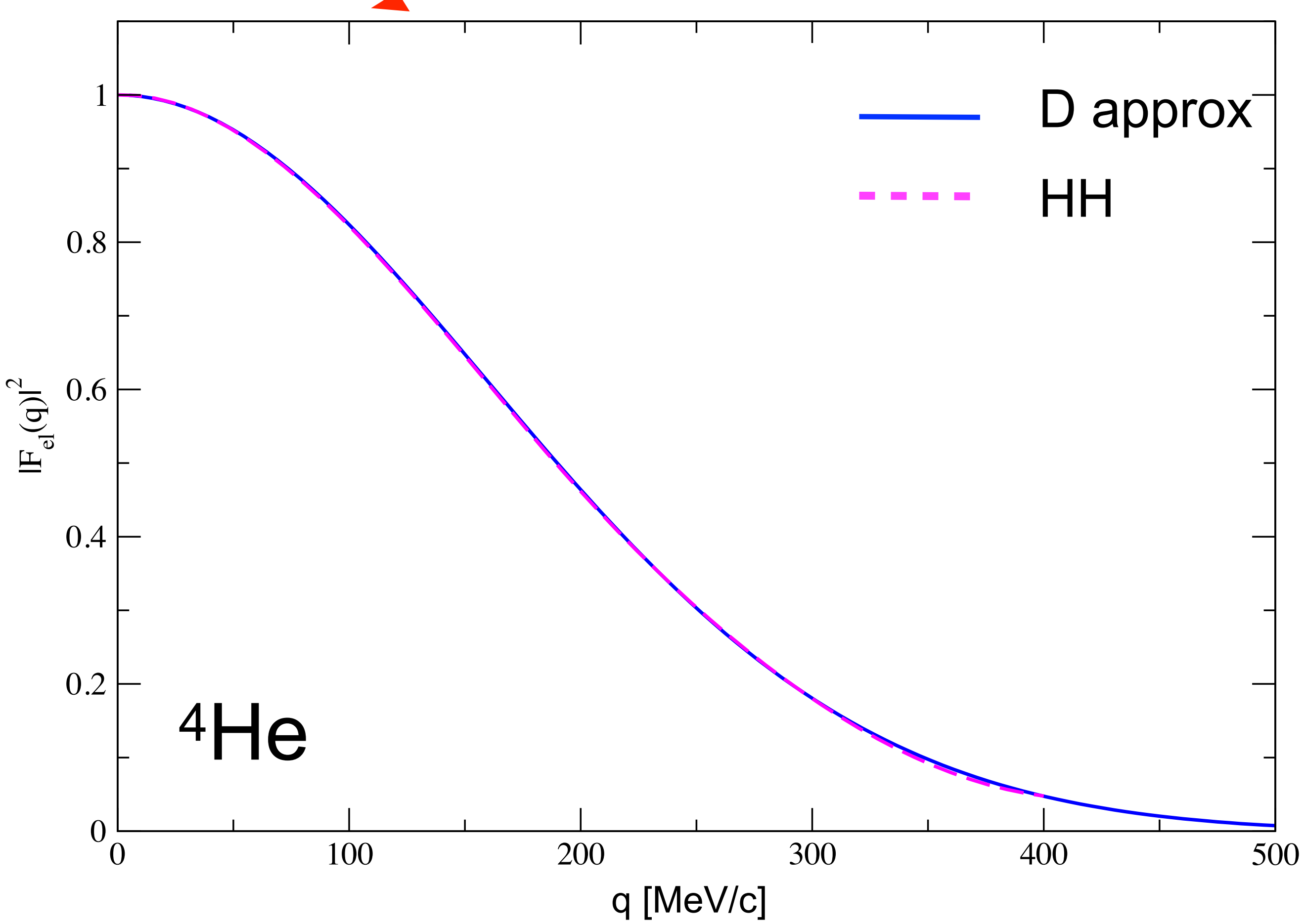
$$\mathrm{CSR}(q) = \int d\omega \; R_L^{in}(\omega, \mathbf{q}) \qquad R_L^{in}(\omega, \mathbf{q}) = \sum_f |\langle f|\rho(\mathbf{q})|\mathbf{0}\rangle|^{\mathbf{2}} \delta(\omega - \mathbf{E_f} + \mathbf{E_0})$$



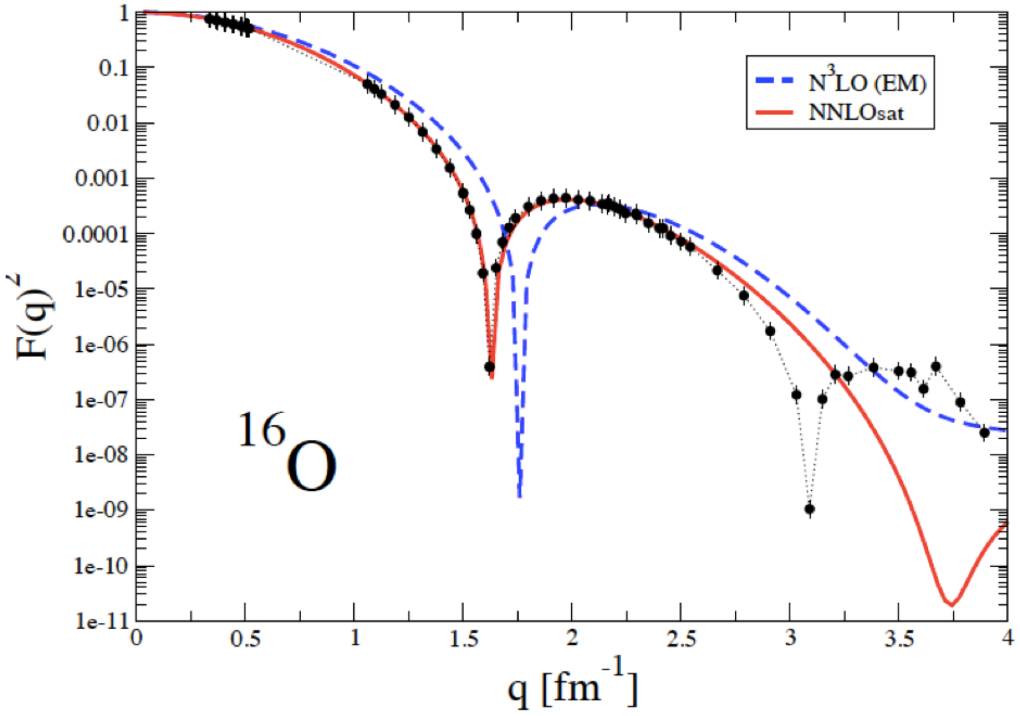
$$\mathrm{CSR}(q) = Z + \langle 0| \sum_{i \neq j} e^{i\mathbf{q}\cdot(\mathbf{r}_i - \mathbf{r}_j)} |0\rangle - |F_{\mathrm{el}}(\mathbf{q})|^2 Z^2$$

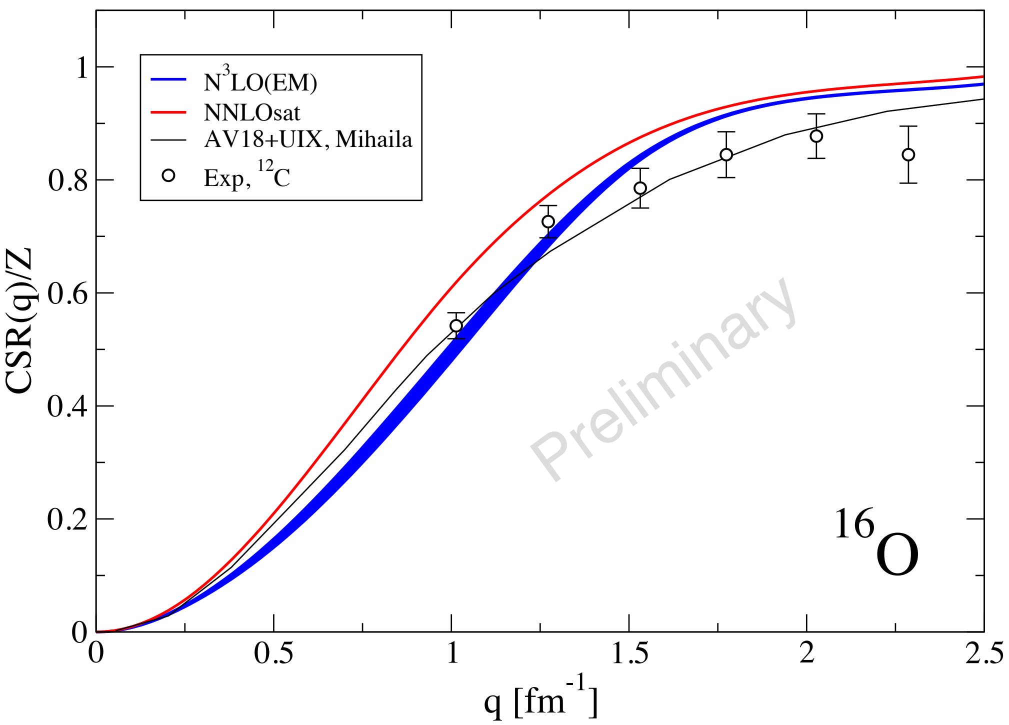
$$\sum_{i \neq j} \langle 0| e^{i\mathbf{q}\cdot(\mathbf{r}_i - \mathbf{r}_j)} |0\rangle = Z(Z-1) f_2(|\mathbf{q}|)$$

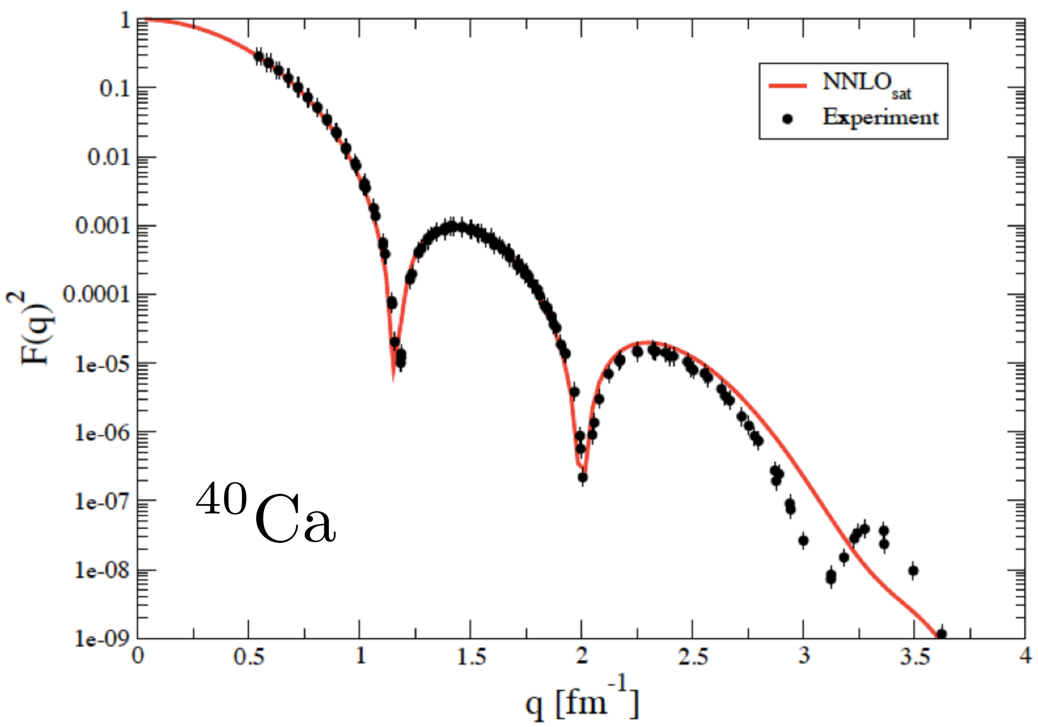


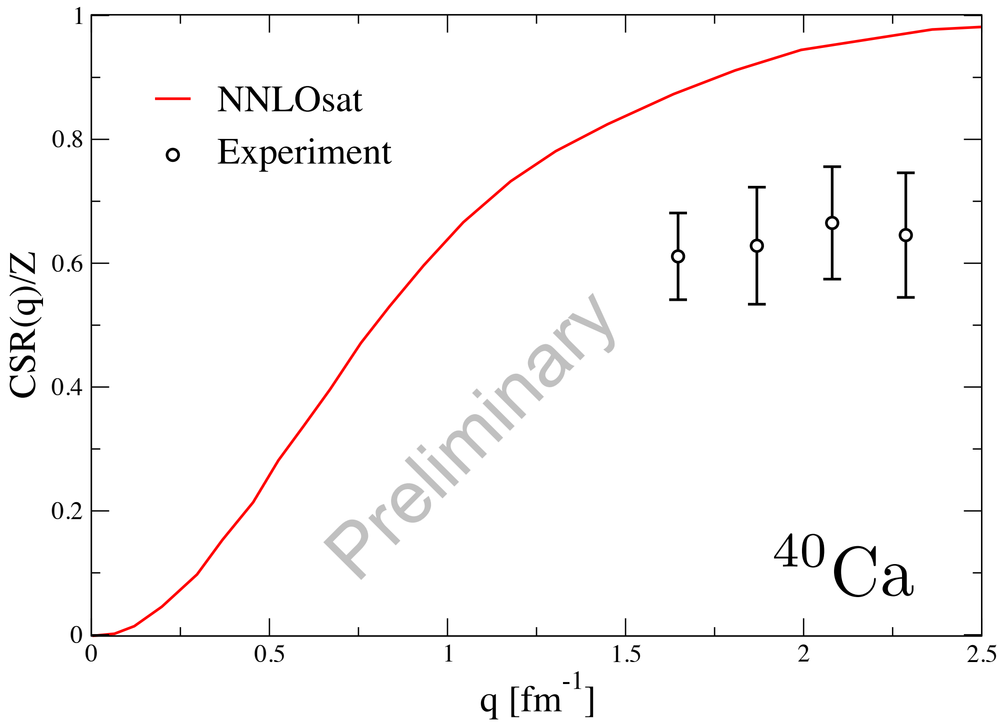


S. Bacca et al., in preparation (2018)









Outlook

- **Triples-correlations:**
  Corrections beyond D in the similarity transformed operator are negligible
  The T-1/D approximation agrees with exact results and coincidentally with D/S

- **Work in progress in analyzing the chiral convergence and the Coulomb sum rule**

- **In the future we plan to address electron-nucleus and neutrino-nucleus scattering**
  B. Acharya

Outlook

- **Triples-correlations:**
  Corrections beyond D in the similarity transformed operator are negligible
  The T-1/D approximation agrees with exact results and coincidentally with D/S

- **Work in progress in analyzing the chiral convergence and the Coulomb sum rule**

- **In the future we plan to address electron-nucleus and neutrino-nucleus scattering**
  B. Acharya

Thanks to all my collaborators

G. Hagen, M. Miorelli, J. Simonis, T. Papenbrock, et al.

Outlook

- **Triples-correlations:**
  Corrections beyond D in the similarity transformed operator are negligible
  The T-1/D approximation agrees with exact results and coincidentally with D/S

- **Work in progress in analyzing the chiral convergence and the Coulomb sum rule**

- **In the future we plan to address electron-nucleus and neutrino-nucleus scattering**
  B. Acharya

Thanks to all my collaborators

G. Hagen, M. Miorelli, J. Simonis, T. Papenbrock, et al.

Thanks for your attention!

Backup

Work from J. Simonis (2018)

NB: Stange behaviour observed at LO with cutoff 550 MeV