Neutrino Theory Network Workshop
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QUANTUM MANY-BODY COMPUTATIONS OF LEPTON-NUCLEUS QUASIELASTIC SCATTERING

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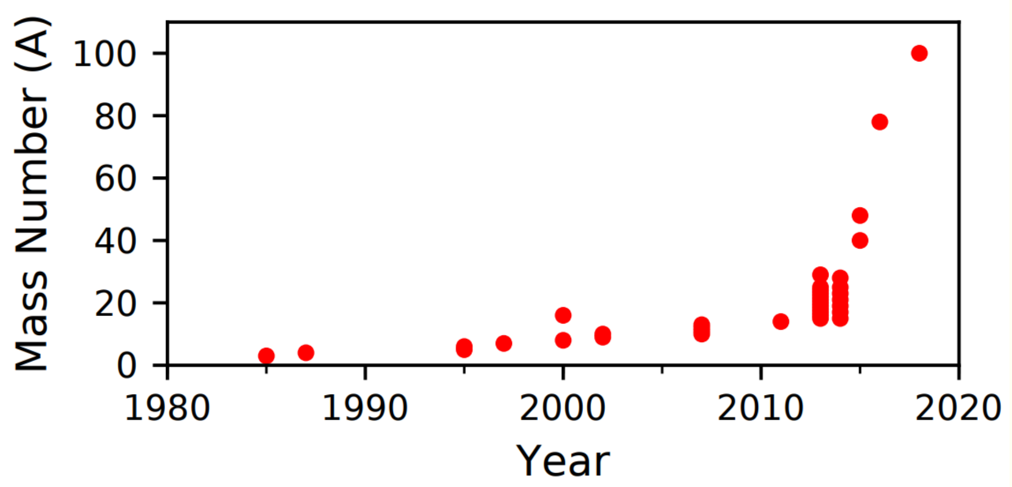
Ab initio nuclear theory

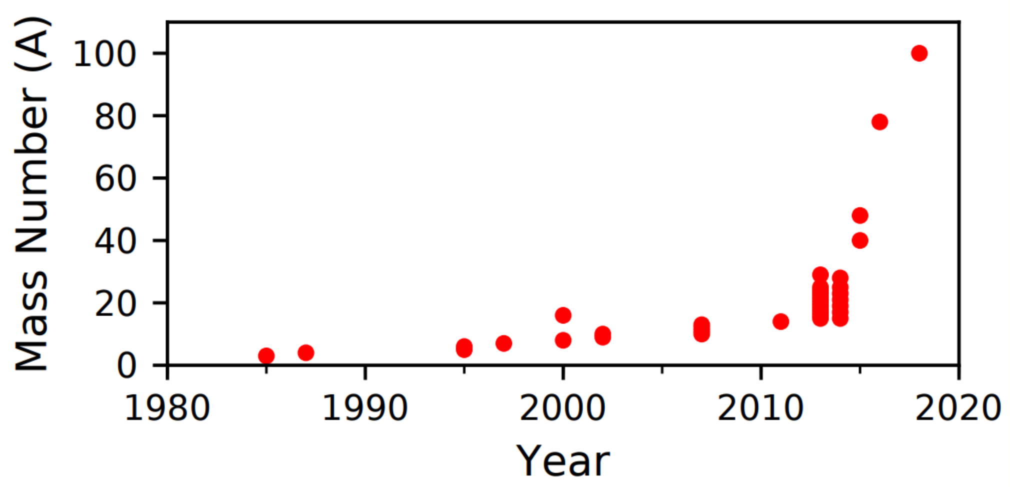
- Solves the A-body Schrödinger equation starting form protons and neutrons
- Includes many-body correlations: is not limited to plane-wave, impulse and mean-field approximations
- Employs nuclear Hamiltonian and electroweak currents that are consistent with each other and with symmetries of QCD & EW theory
- Makes only controlled approximations:
  - allows uncertainty quantification
  - is systematically improvable



J Simonis, S Bacca and G Hagen, Eur. Phys. J. A ***55*** *(2019) 241*

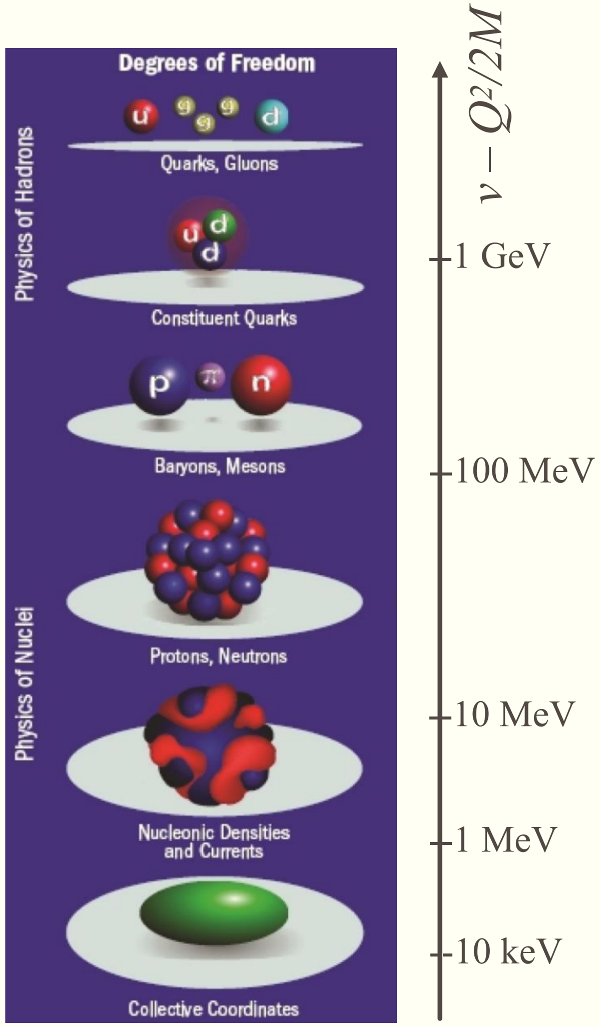
Ab initio nuclear theory

- **not** *ab initio*:
  - Shell Model
  - (Traditional) Hartree-Fock
- *ab initio* (**exponential** scaling with A):
  - No-Core Shell Model
  - Green's Function Monte Carlo
- *ab initio* (**polynomial** scaling with A):
  - **Coupled Cluster**
  - In-Medium Similarity Renormalization Group
  - Self-Consistent Green's Function
  - Auxiliary Field Diffusion Monte Carlo

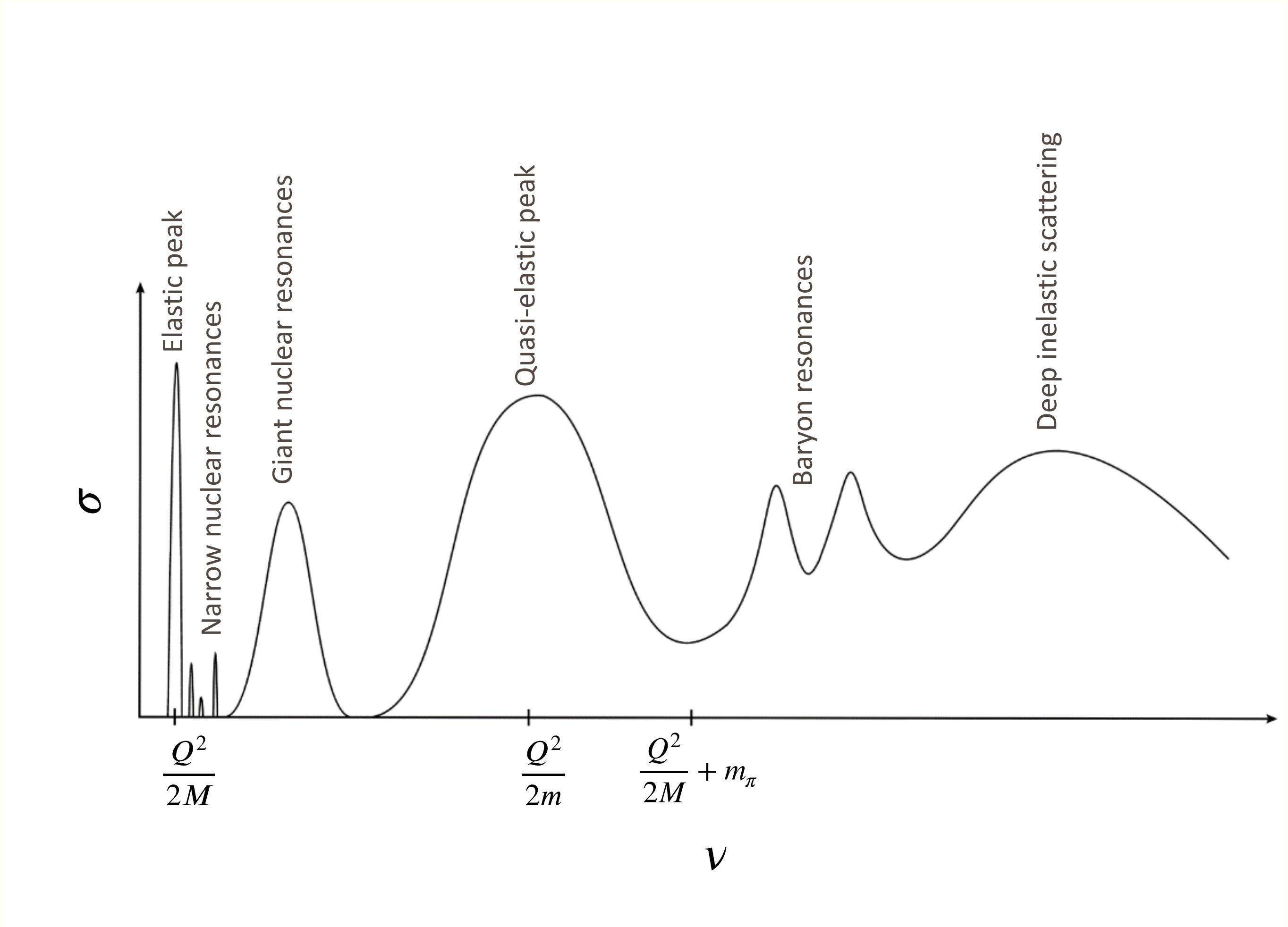


J Simonis, S Bacca and G Hagen, Eur. Phys. J. A ***55*** *(2019) 241*

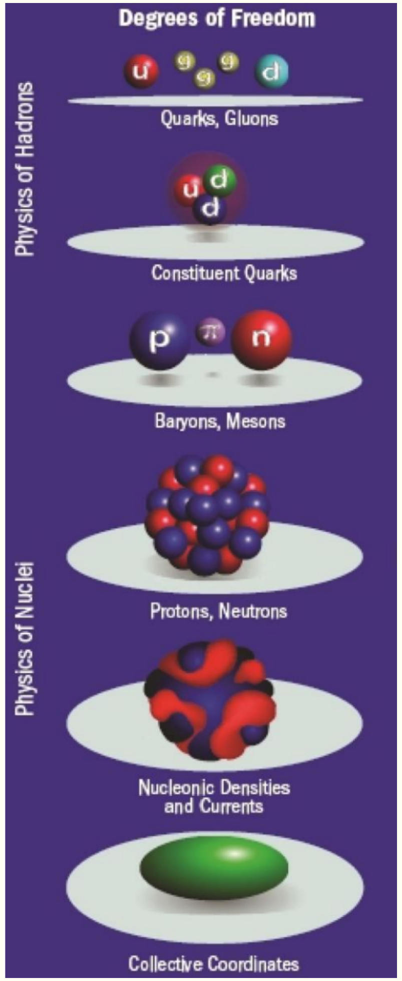
How does a nucleus look to a lepton?



Nazarewicz, J. Phys. G **43** *(2016) 044002*



Chiral effective field theory (χEFT)



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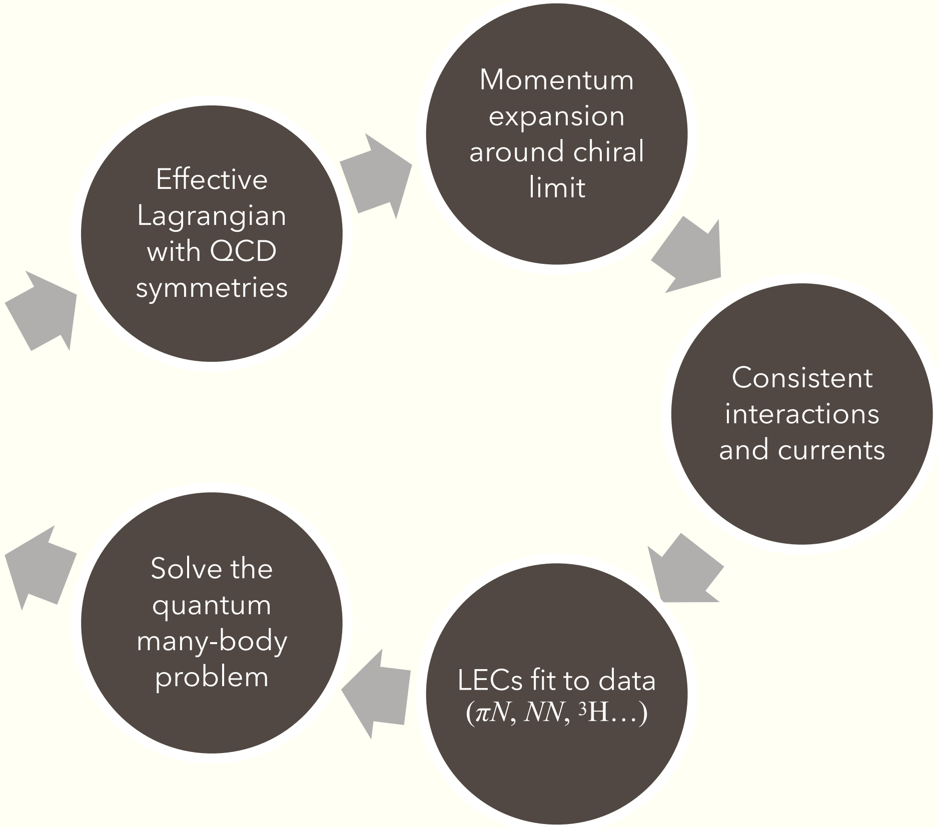
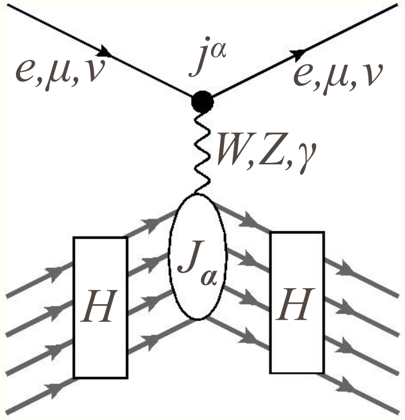




Nuclear electroweak response functions

- Vector part of the weak current, $J_\alpha \equiv V_\alpha + A_\alpha$, tested on electron-scattering data

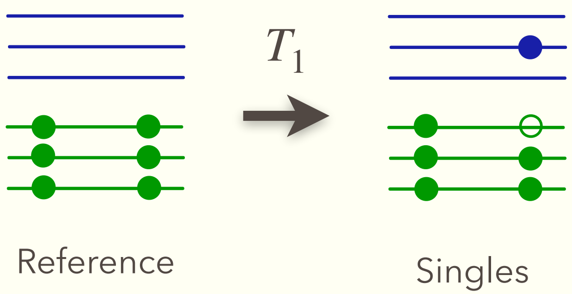
$$\left.\frac{d\sigma}{d\Omega\, dq}\right|_{\nu/\bar{\nu}} = v_{00}R_{00} - v_{0z}R_{0z} + v_{zz}R_{zz} + v_{xx}R_{xx} \mp v_{xy}R_{xy}$$

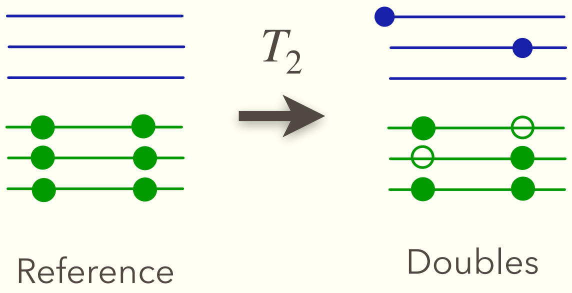
$$\left.\frac{d\sigma}{d\Omega\, dq}\right|_{e^-} = v_L R_L + v_T R_T$$

- Response functions contain all information about the nuclear system and can also be compared with other observables (photodissociation, muon capture ...)

$$R_{\alpha\beta}(\nu, q) = \sum_f \langle \Psi | J_\alpha^\dagger | \Psi_f \rangle \langle \Psi_f | J_\beta | \Psi \rangle \, \delta(E_f + q^2/2M - E - \nu)$$

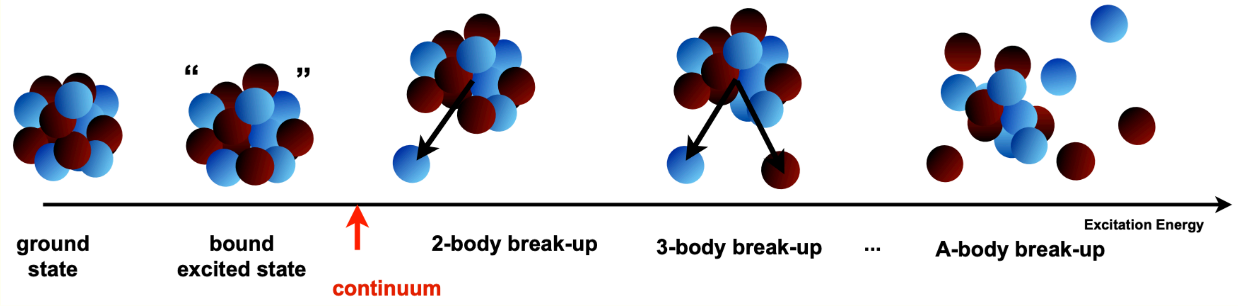
Coupled-cluster theory





- Solves the A-body Schrödinger equation by normal ordering with respect to a mean-field reference state
- The reference state is just a starting point for an expansion
- Exact solution (for employed Hamiltonian and Hilbert space) obtained if one includes all excitations up to T_A. Often truncated at T_2 (and part of T_3 when needed)

The Lorentz integral transform method

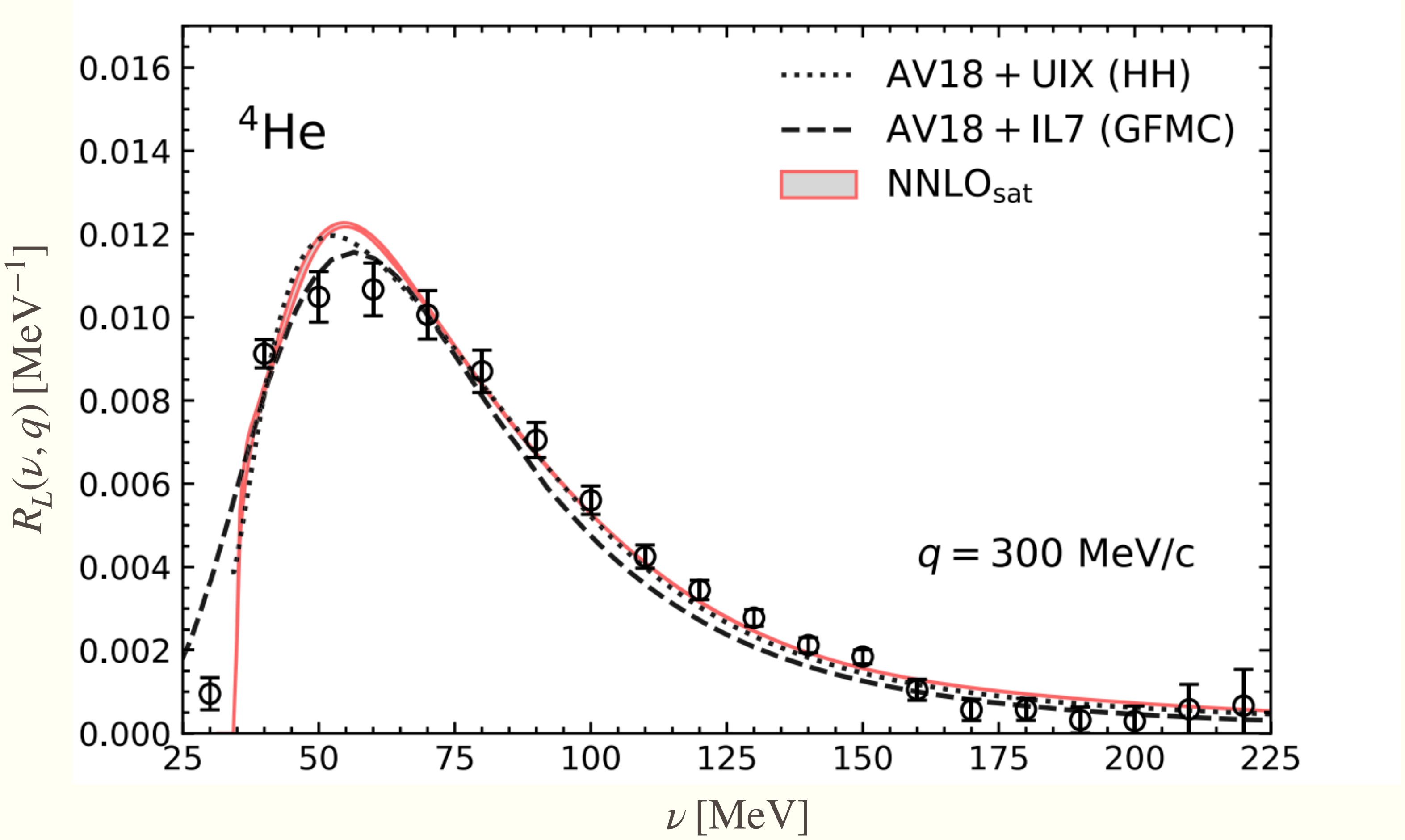


$$R(\nu, q) = \sum_f \langle \Psi | J^\dagger(q) | \Psi_f \rangle \langle \Psi_f | J(q) | \Psi \rangle \, \delta(E_f + q^2/2M - E - \nu)$$

- Define an integral transform $I_\lambda(\sigma, q) = \int d\nu \, \frac{\lambda}{\pi} \frac{1}{(\nu - \sigma)^2 + \lambda^2} R(\nu, q)$
- Can calculate $I_\lambda(\sigma, q)$ as a ground-state expectation value
- Invert $I_\lambda(\sigma, q)$ to obtain the response $R(\nu, q)$

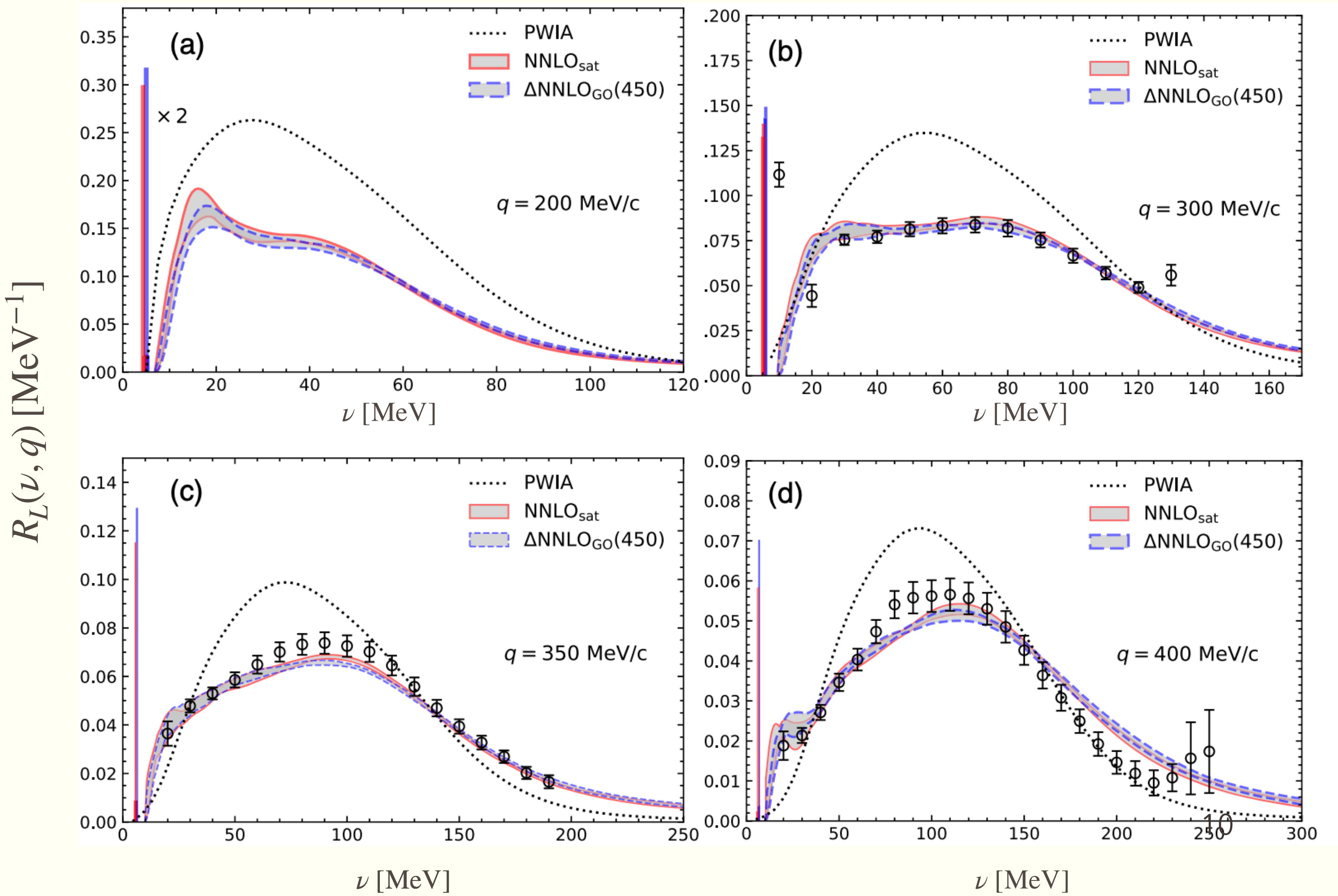
Longitudinal electromagnetic response function: ^{4}He

J E Sobczyk, BA, S Bacca and G Hagen, Phys. Rev. Lett. ***127*** *(2021) 072501*



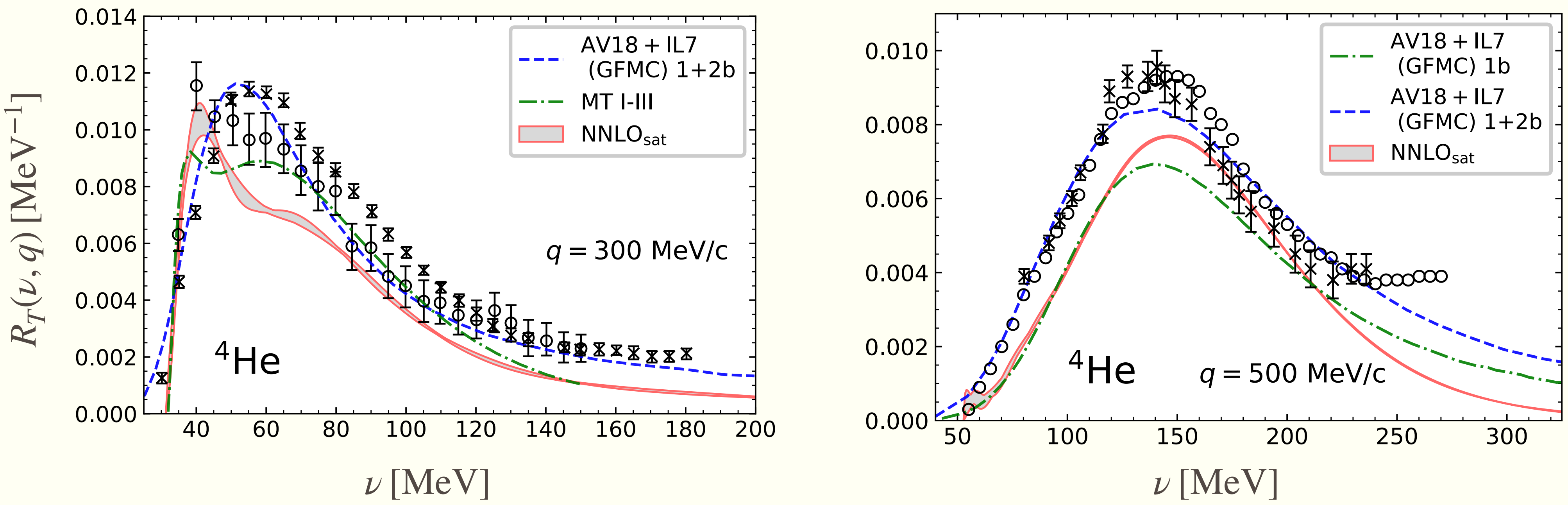
Longitudinal electromagnetic response functions: $^{40}\mathrm{Ca}$

*J E Sobczyk, BA, S Bacca and G Hagen, Phys. Rev. Lett. **127** (2021) 072501*



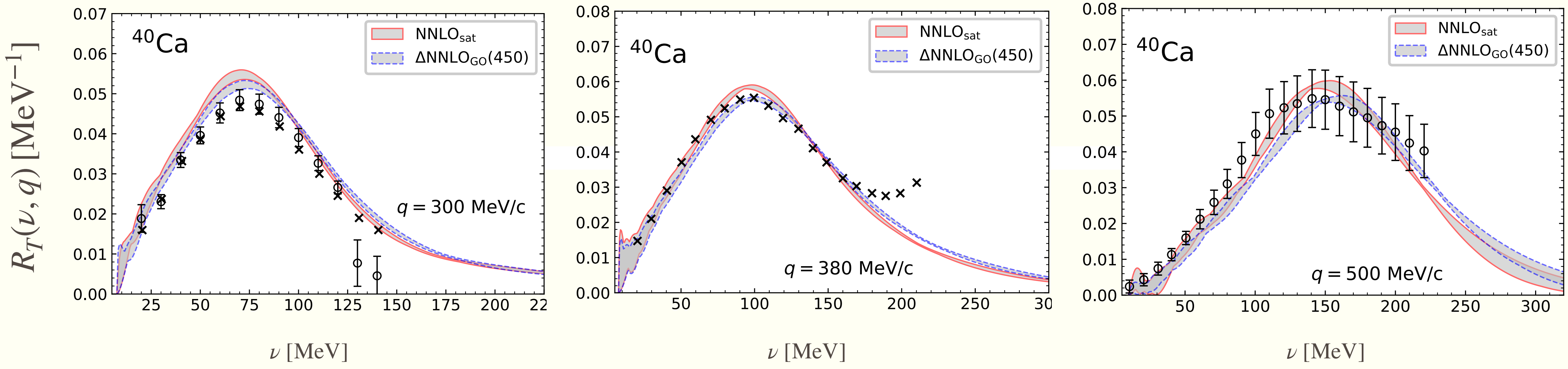
1-body transverse electromagnetic response functions: ^{4}He

BA, J E Sobczyk, S Bacca and G Hagen, In Preparation



1-body transverse electromagnetic response functions: ^{40}Ca

BA, J E Sobczyk, S Bacca and G Hagen, In Preparation



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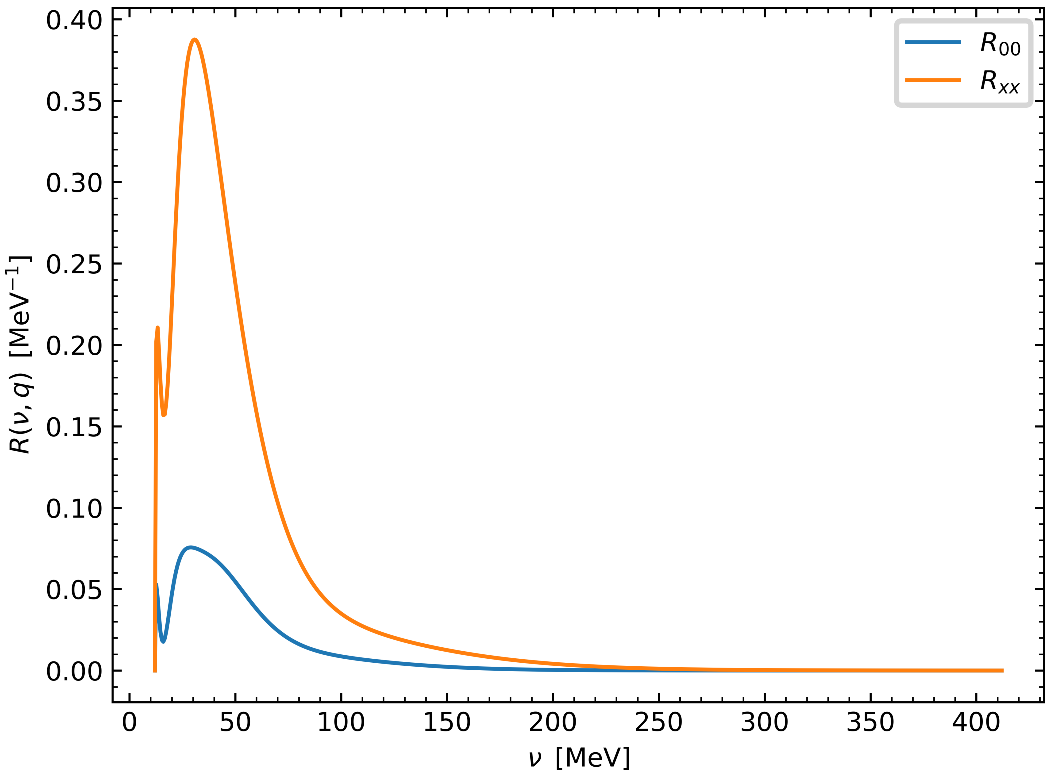
1-body weak response functions: $\nu + {}^{16}\mathrm{O} \rightarrow l^- + {}^{16}X^+$

BA, J E Sobczyk, S Bacca and G Hagen, In Preparation



Current and near-future directions

- Extension to the $^{40}\mathrm{Ar}$ nucleus: projection after variation vs double-charge-exchange EoM vs fractional occupation number…

*C G Payne, S Bacca, G Hagen et al., Phys. Rev. C **100** (2019) 061304(R)*
G Hagen et al., arXiv:2201.07298 (2022)

- Include matrix elements of 2-body currents: derived and tested to high precision

*BA and S Bacca, Phys. Rev. C **101** (2020) 015505*
*BA, V Lensky, S Bacca et al., Phys. Rev. C **103** (2021) 024001*
*BA and S Bacca, Phys. Lett. B **827** (2022) 13701*

- Addressing needs of experiment/event generators:
    - fast and accurate emulators
    - Bayesian Model Mixing with other theories (*e.g.* extended factorization scheme, relativistic mean field) to include relativistic effects …
    - exclusive channels

- Novel alternatives to the integral transform *BA and X Zhang, In Preparation*