Towards ab initio computations of neutrino-nucleus cross sections

Bijaya Acharya
Neutrino Theory Network Fellow
Oak Ridge National Laboratory

Jun 29, 2023

Collaborators

- Joanna E **Sobczyk** (Mainz)
- Sonia **Bacca** (Mainz)
- Gaute **Hagen** (ORNL, UTK, TRIUMF)
- Thomas **Papenbrock** (UTK, ORNL)

Outline

- "Ab initio" computations in low-energy nuclear physics
- Chiral effective field theory (χEFT)
- Coupled-cluster (CC) theory
- The Lorentz integral transform (LIT) method
- LIT-CC results for the quasielastic electron-scattering responses $R_{L,T}(\omega, q)$
- Quasielastic neutrino-scattering responses with 1-body (1B) currents
- Role of 2-body (2B) currents in magnetic dipole transitions in $^{48}\mathrm{Ca}$ and relevance for $\mathcal{O}(10\,\mathrm{MeV})$ neutrinos

“Ab initio” nuclear theory

- Quantum Chromodynamics (QCD) is intractable at nuclear energies except for the smallest systems

- Phenomenological descriptions employing hadronic degrees of freedom (that antedate the discovery of quarks!) have been highly successful

- This phenomenological approach can be connected to QCD through ideas from Effective Field Theories and Renormalization Group methods

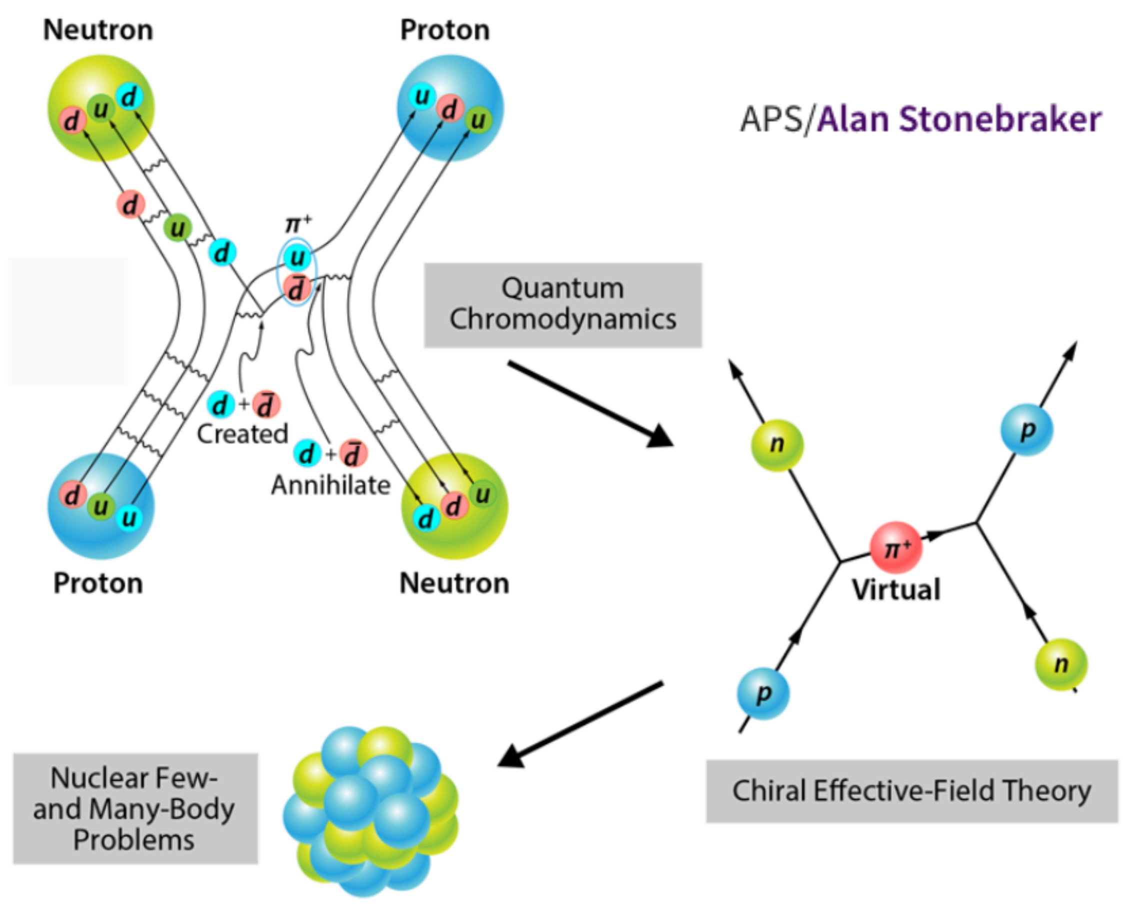
- In this talk, “ab initio” = “systematically improvable approach with controlled uncertainties that maintains closest possible link to the Standard Model interactions while maximizing predictive capabilities”

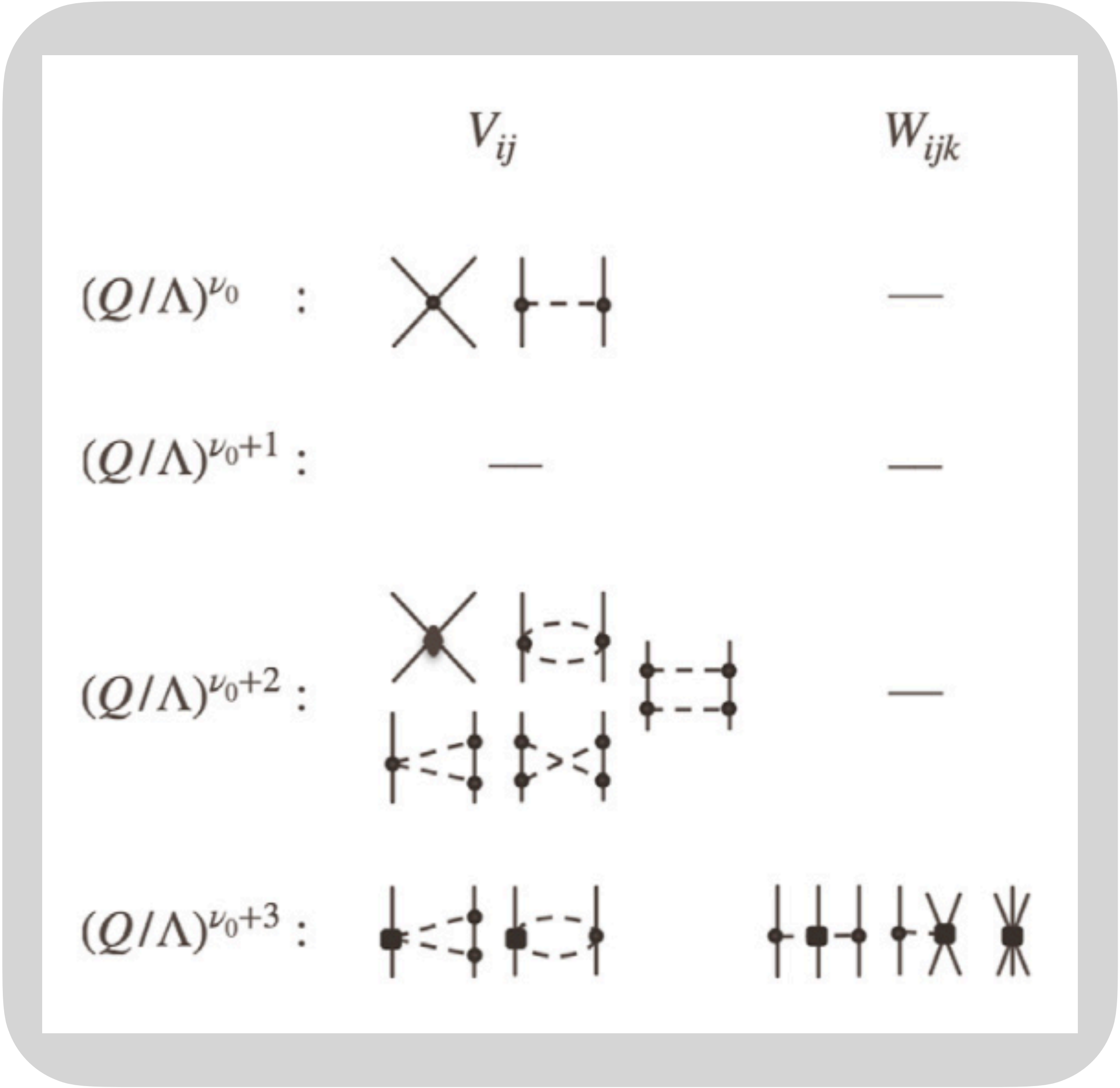
Ekström et al., What is ab initio in nuclear theory?, *Front. Phys.* ***11*** *(2023) 1129094.*

Chiral effective field theory (χEFT)

Ekström, Piarulli, Baroni, Pastore, Epelbaum, Krebs, Meissner, van Kolck, Schiavilla, Machleidt, Kaplan, Savage, Wise, Weinberg, …

- Work with n and p that interact with each other and with e^-, ν through χEFT interactions
- Order-by-order expansion of Standard Model interactions in powers of Q/Λ
- Valid at low momenta Q below $\Lambda \sim 700\ \mathrm{MeV}$
- Underlying quark-gluon physics shows up as values of low-energy constants, which are fit to data (NN, πN…)
- Theory uncertainty from the neglected higher-order terms can be estimated





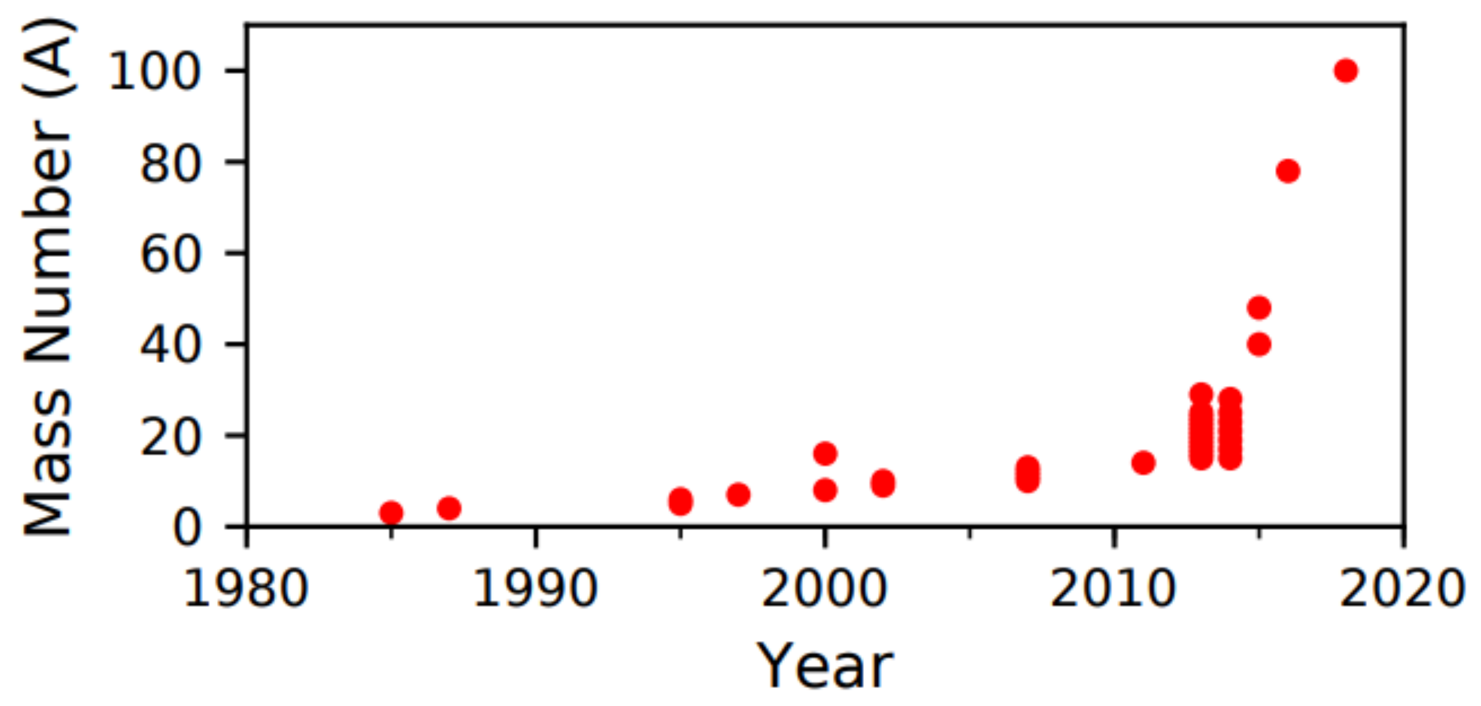
Coupled-cluster theory

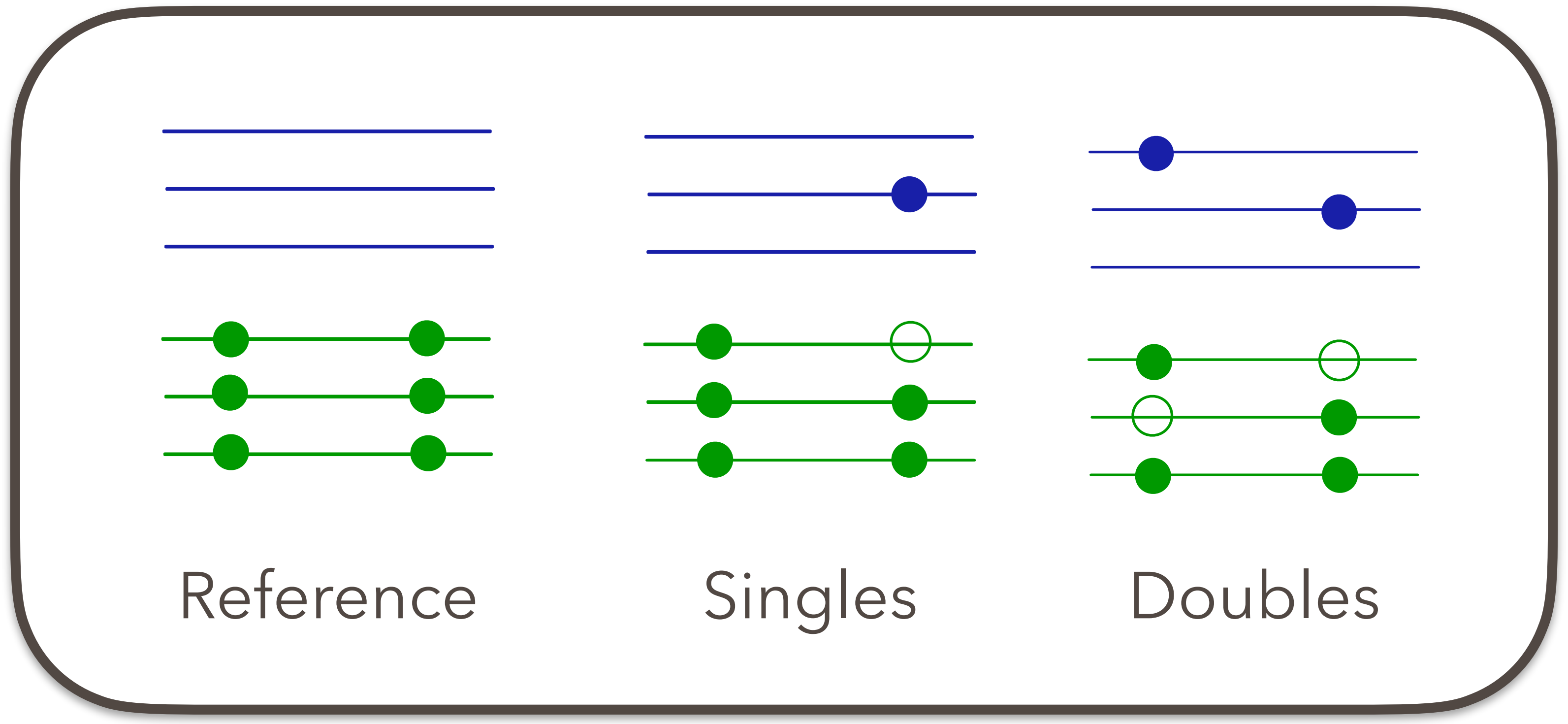
Koester, Kümmel, Bartlett, Papenbrock, Dean, Hagen, …

- Is part of an active community-wide effort to go beyond mean-field approximations at affordable computational cost

- Approaches the exact solution of the many-body Schrödinger equation through particle-hole excitations around a reference (a single Slater determinant)

- Allows us to choose the reference state, go to higher order in the particle-hole expansion …





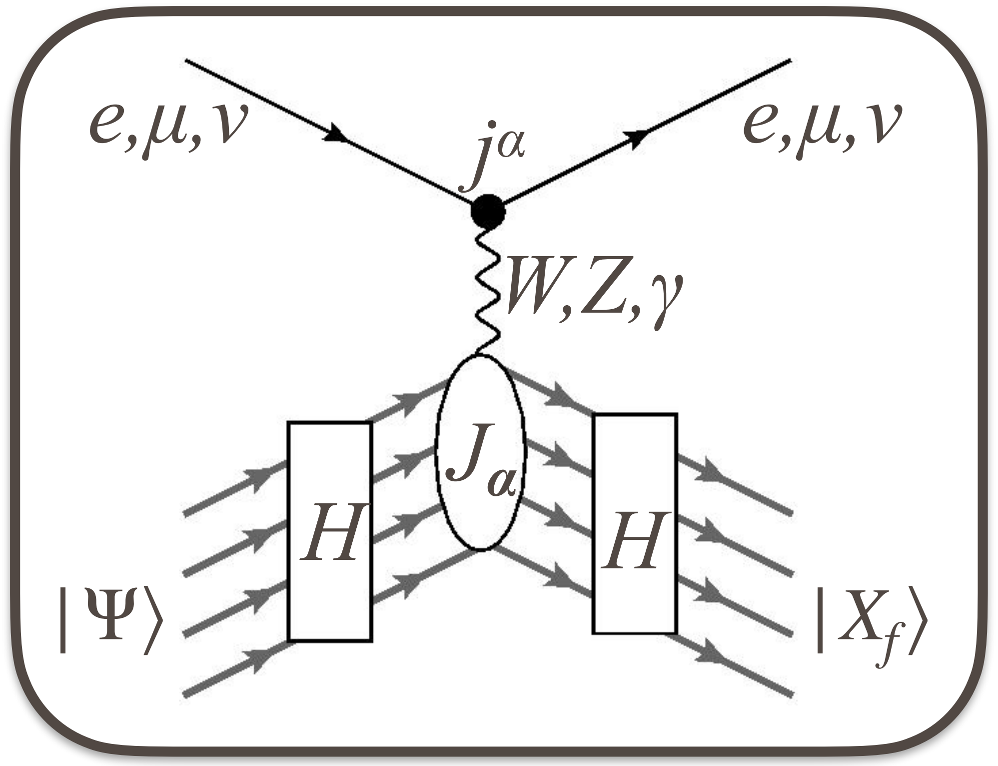
Milestone

Ab initio coupled-cluster approach to nuclear structure with modern nucleon-nucleon interactions

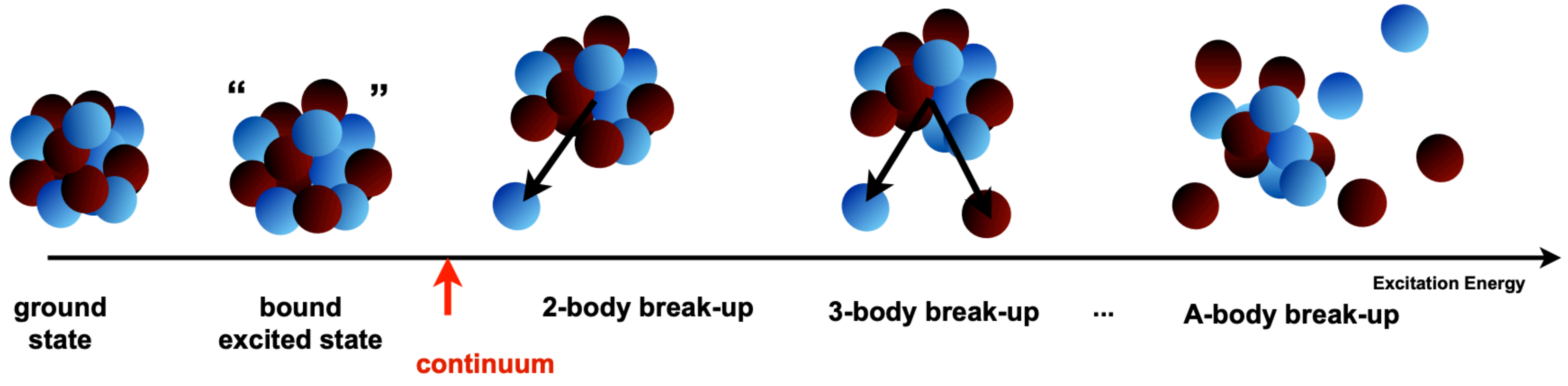
G. Hagen, T. Papenbrock, D. J. Dean, and M. Hjorth-Jensen
Phys. Rev. C **82**, 034330 – Published 30 September 2010

An article within the collection: *Physical Review C* 50th Anniversary Milestones

eA and νA cross sections in the LIT-CC method



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



We evaluate $R(\omega, q) = \sum_f \langle \Psi | J^\dagger(q) | X_f \rangle \langle X_f | J(q) | \Psi \rangle \, \delta(E_f + q^2/2M - E - \omega)$ w/o calculating $|X_f\rangle$

- Define an integral transform $I_\Gamma(\sigma, q) = \int d\omega \, \frac{\Gamma}{\pi} \frac{1}{(\omega - \sigma)^2 + \Gamma^2} R(\omega, q)$

- Calculate $I_\Gamma(\sigma, q)$ as a ground-state expectation value and invert it to obtain the response $R(\omega, q)$, e.g., by a basis expansion of $R(\omega, q)$

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

Ab initio neutrino-nucleus cross sections

We have overcome several key technical challenges:

✓ Multipole decomposition of 1B and 2B χEFT electroweak currents

BA and Bacca, Phys. Rev. C ***101*** *(2020) 015505*

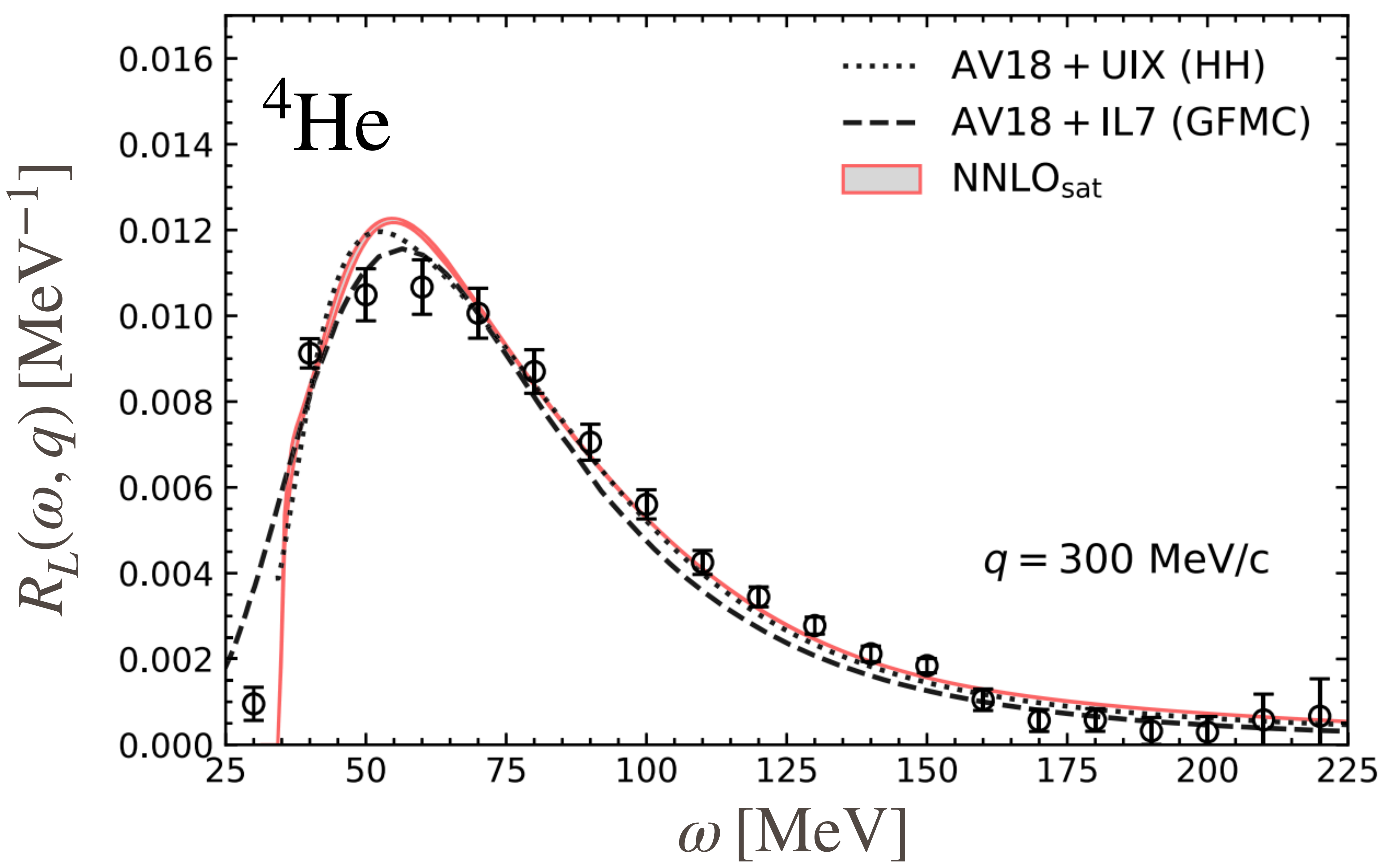
✓ Removal of spurious center-of-mass excitations

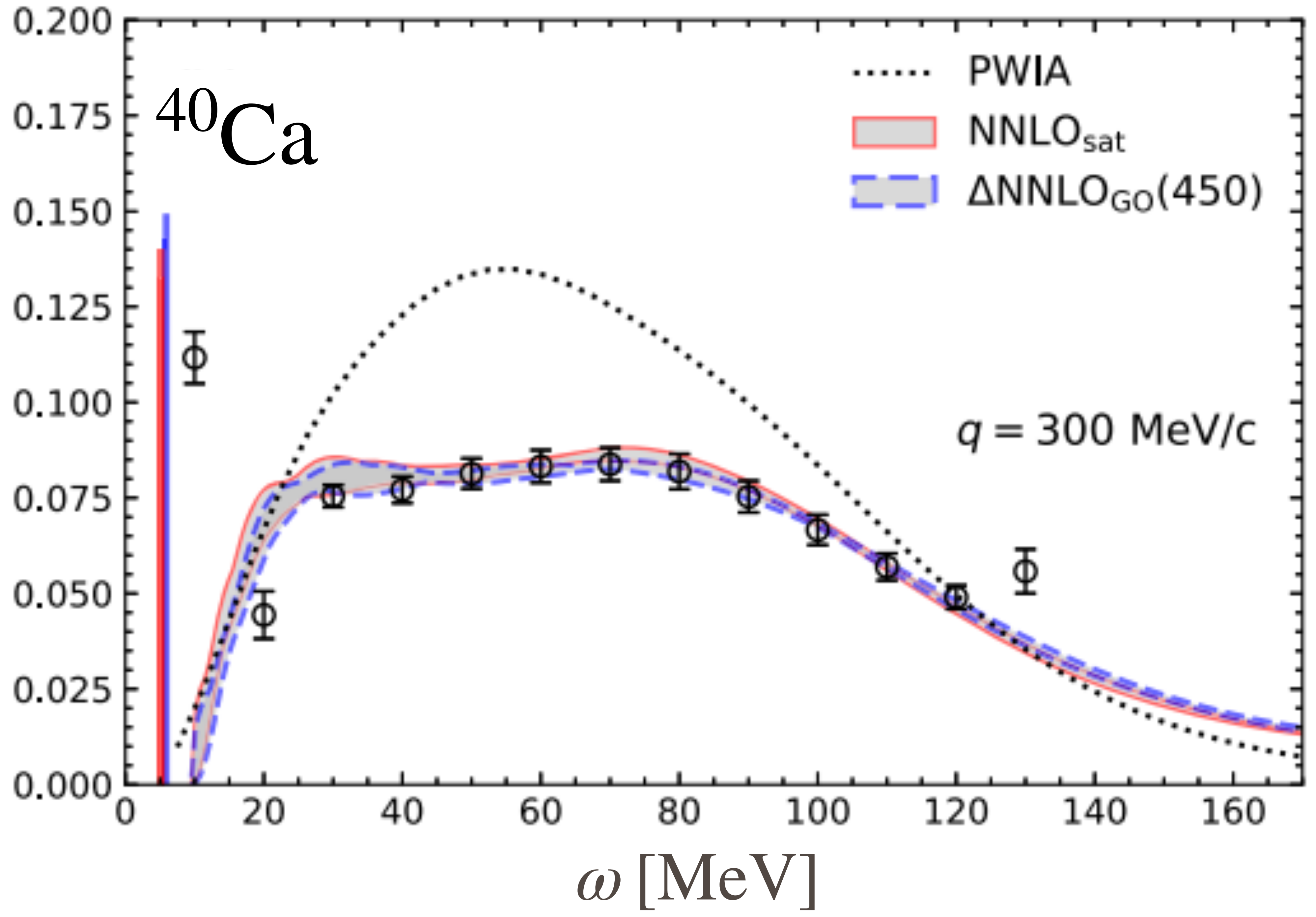
Sobczyk, BA, Bacca and Hagen, Phys. Rev. C ***102*** *(2020) 064312*

✓ Transformation of the matrix elements of the 2B χEFT electroweak currents to the reference frame and basis used in many-body computations

BA et al., In Preparation

Longitudinal electron-scattering responses



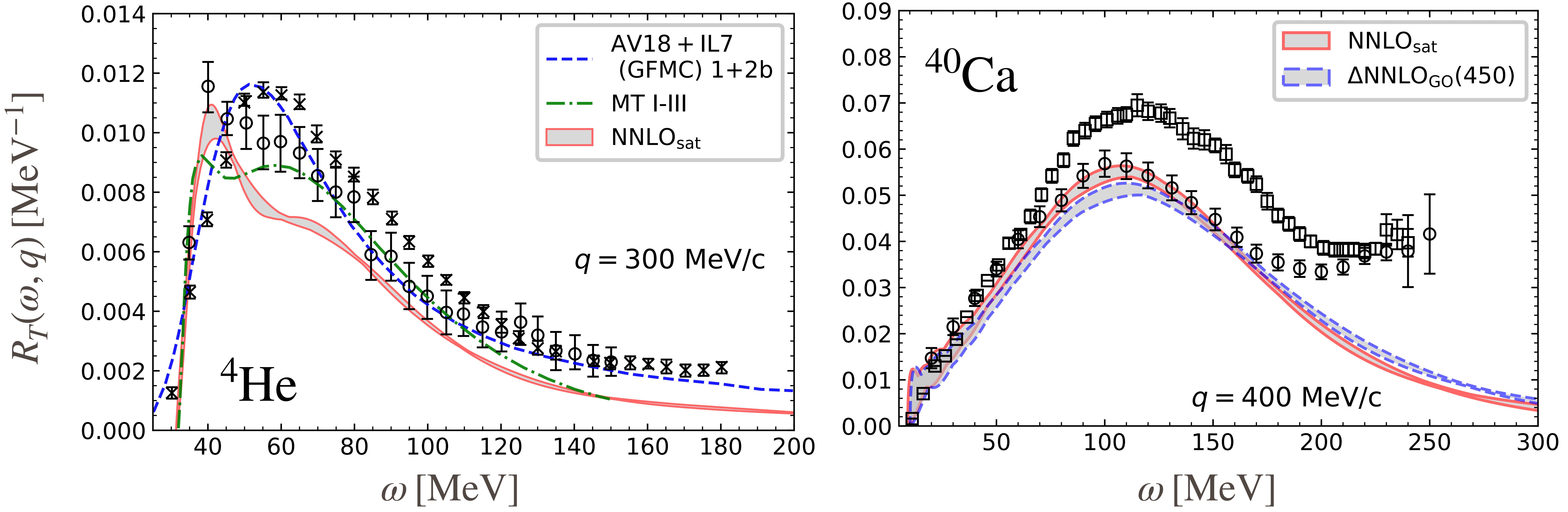


Sobczyk, BA, Bacca and Hagen, Phys. Rev. Lett. ***127*** *(2021) 072501*

- Bands reflect the many-body-theory and LIT-inversion uncertainties
- 2B currents do not appear (until we go to much higher orders in the χEFT expansion)
- Plane-wave impulse approximation (PWIA) misses ^{40}Ca data: final-state interactions important

Transverse electron-scattering responses (with 1B currents)

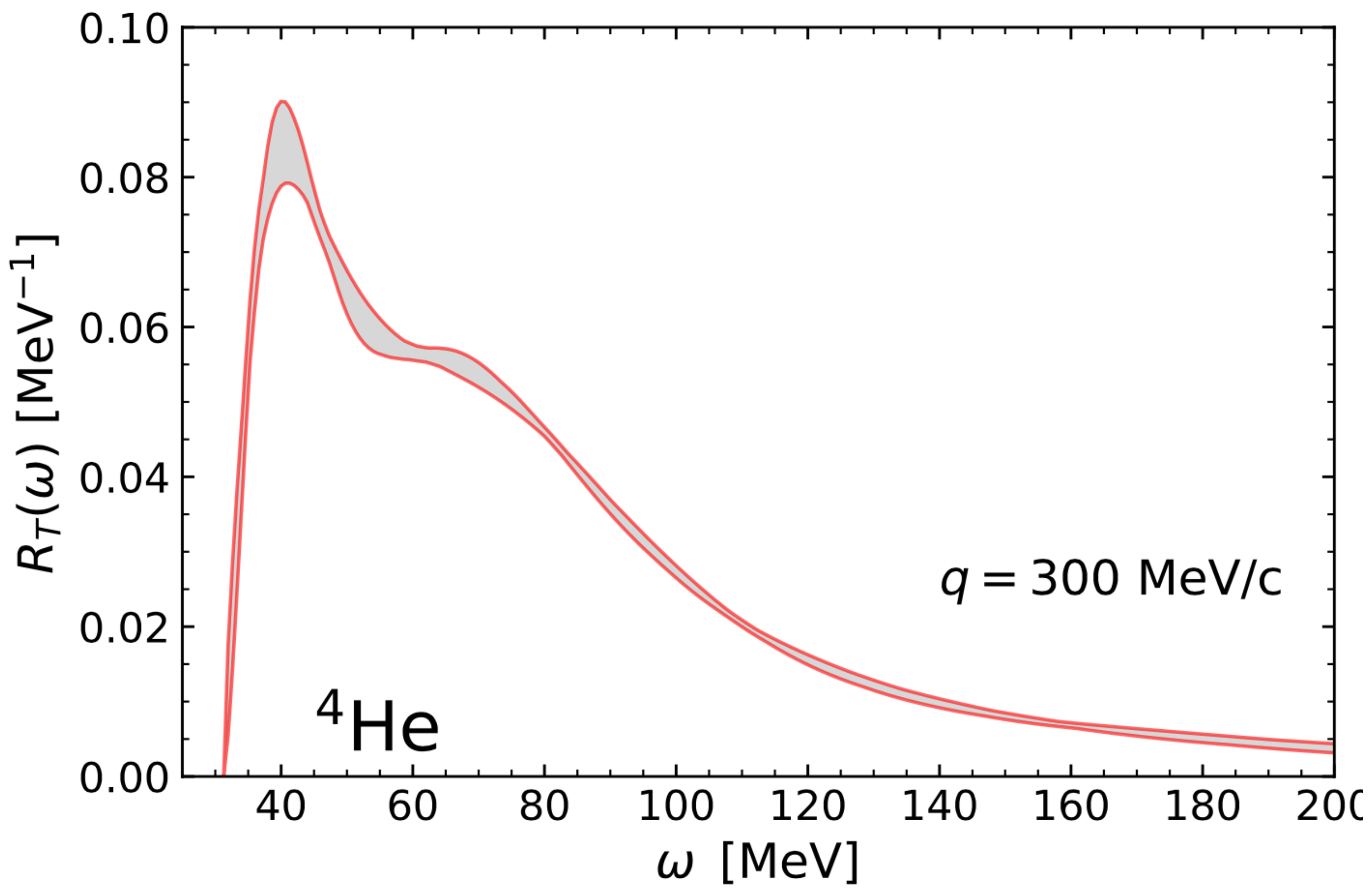
Sobczyk, BA, Bacca and Hagen, In preparation

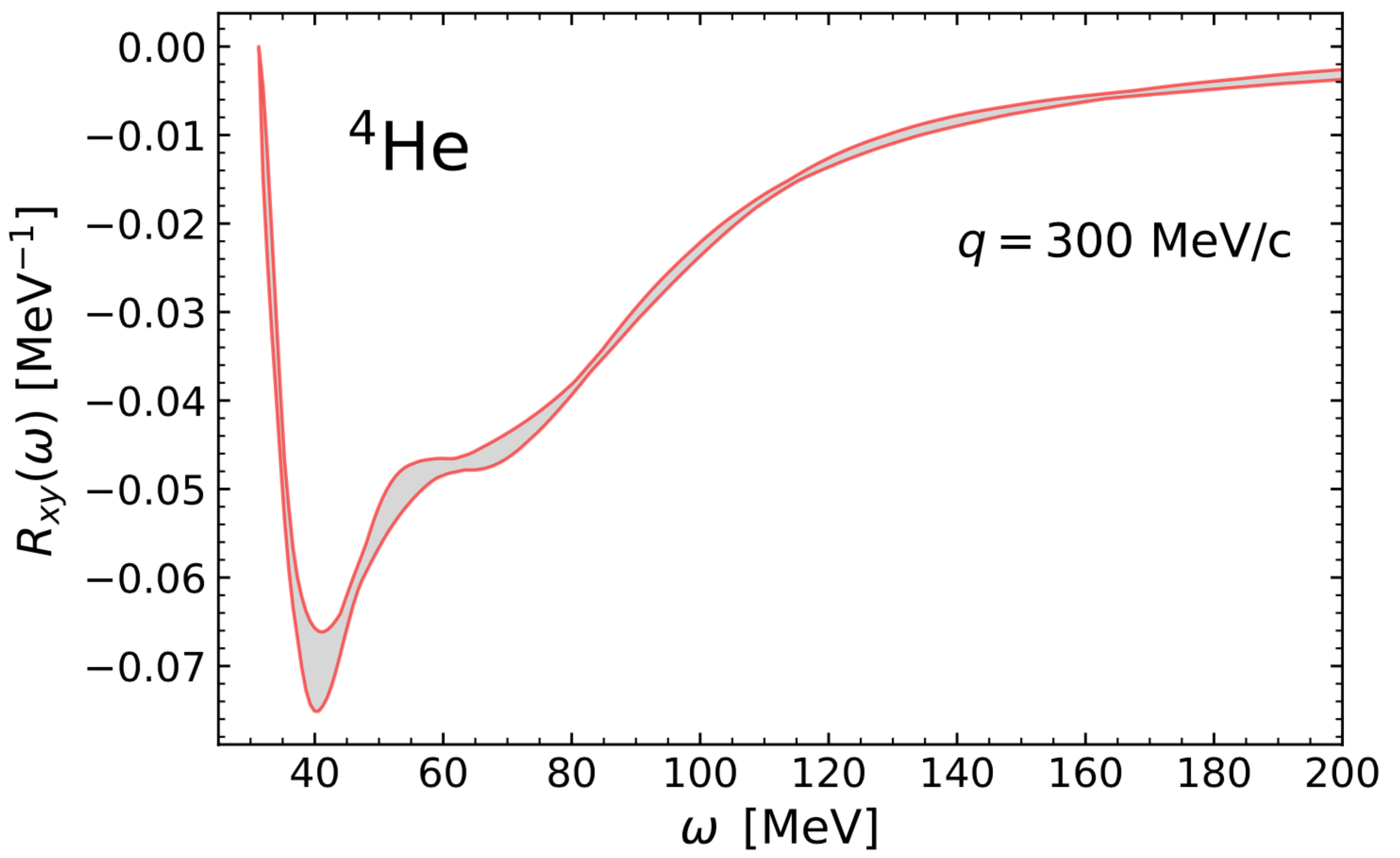


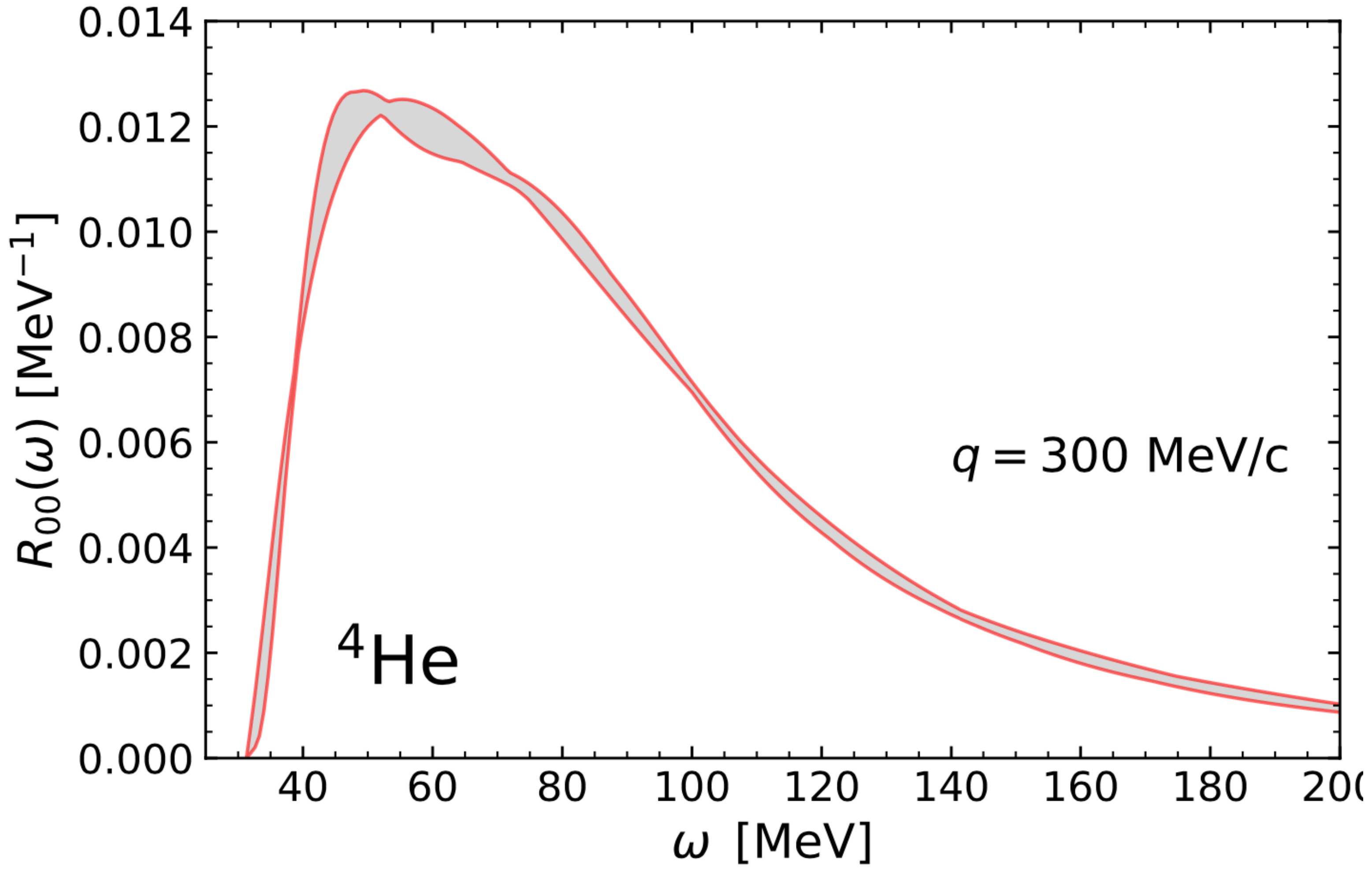
- Results for ^{4}He are consistent with anticipated size of missing 2B current contributions
- Good agreement for ^{40}Ca already with just 1B currents; possible that we will overshoot data one 2B currents are included

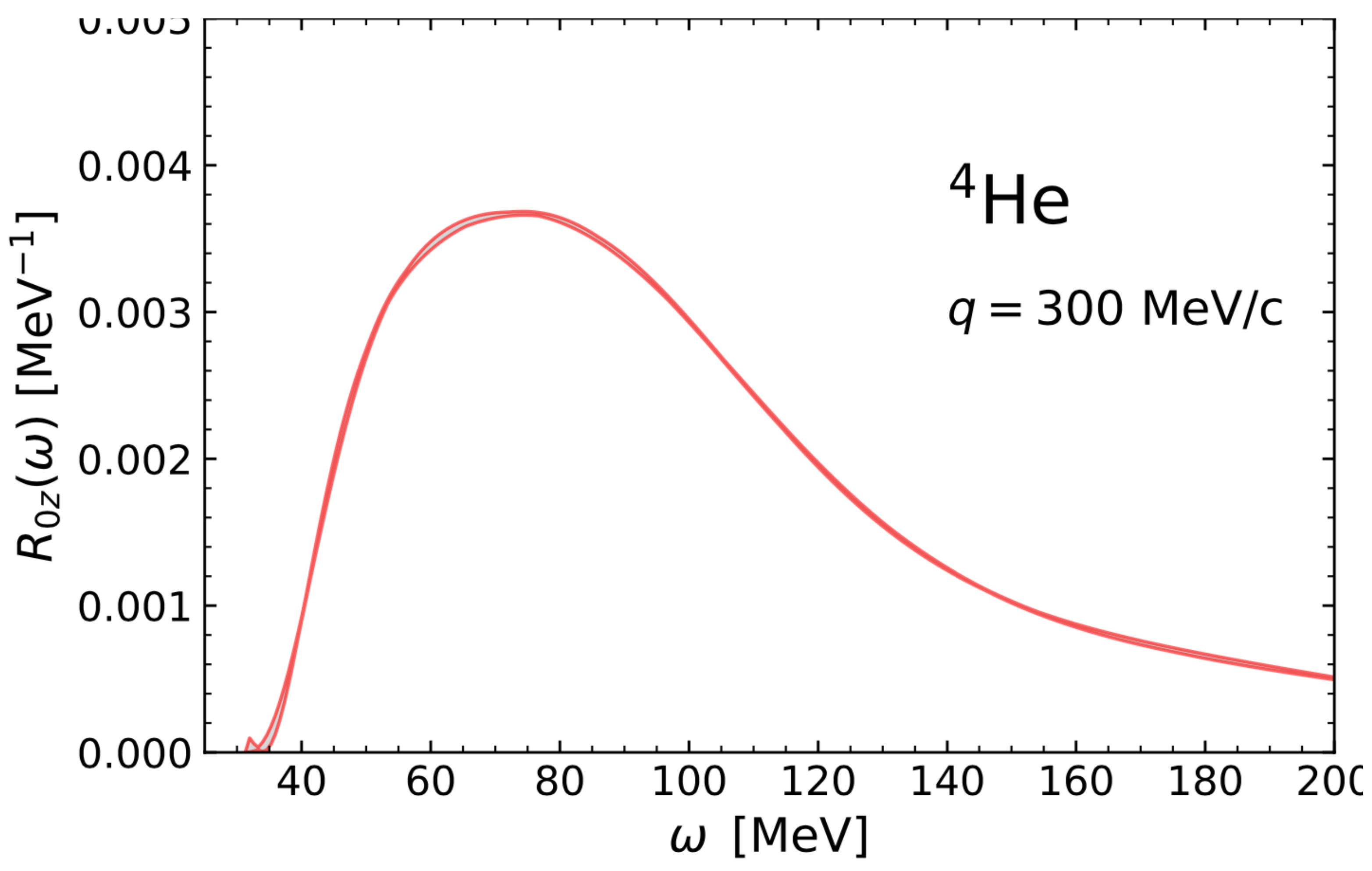
$\nu_e + {}^4\mathrm{He} \rightarrow e^- + {}^4\mathrm{X}$

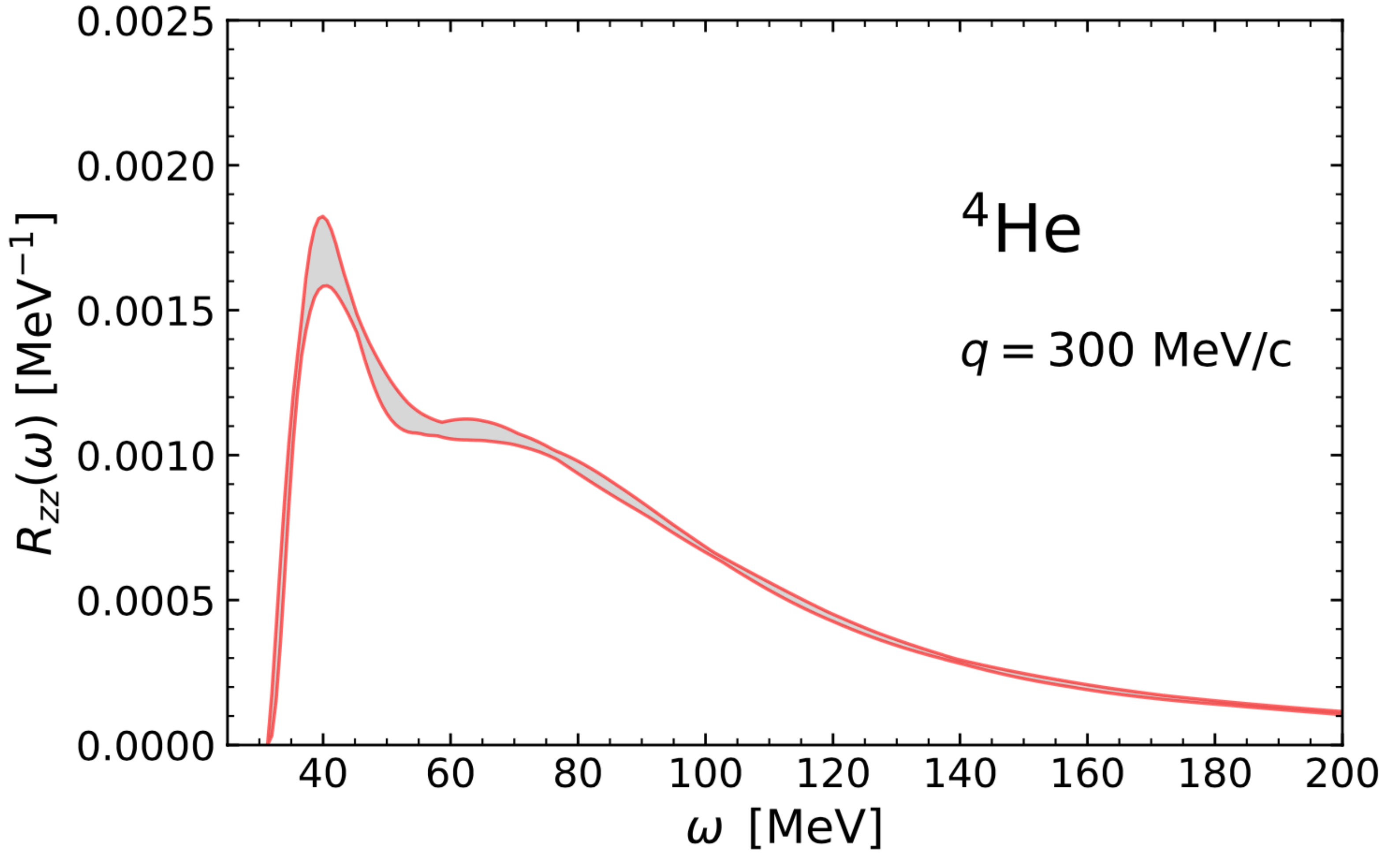
- Results for $\mathrm{NNLO_{sat}}$ interactions with 1B currents
- Many-body uncertainty is under control and can be further reduced.







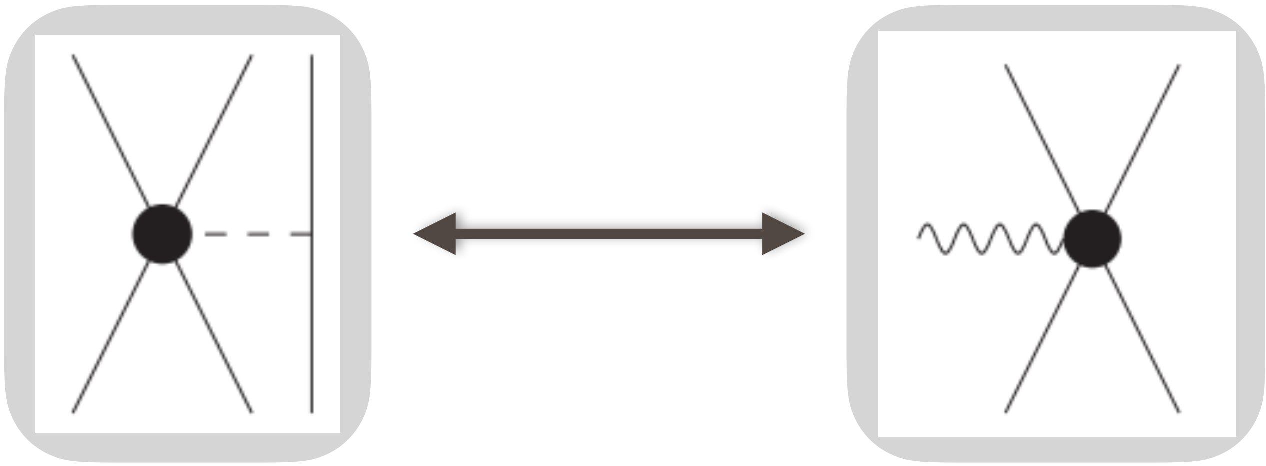




BA et al., In preparation

Two-body electroweak currents in χEFT

- Many-body currents automatically emerge in χEFT, just like many-body forces, and must be included if demanded by power-counting
- Current conservation relates the 2B vector currents to the strong interaction Hamiltonian: $q^\mu \langle \psi_f | J_\mu | \psi_i \rangle = 0 \Leftrightarrow [H, \rho] = \mathbf{q} \cdot \mathbf{J}$
- Even the 2B axial current is directly connected to H in χEFT:



c_D $\quad$ d_R

2B currents, magnetic dipole (M1) and Gamow-Teller (GT) transitions, and neutrinos

- The 1B M1 operator bears strong resemblance to the 1B GT operator:

$$\boldsymbol{\mu}_{1\mathrm{B}} = \frac{1}{2}\sum_{i=1}^{A} \mu_n \boldsymbol{\sigma}_i [1 + \tau_i^{(z)}] + (\boldsymbol{\ell}_i + \mu_p \boldsymbol{\sigma}_i)[1 - \tau_i^{(z)}] \,,$$

- This resemblance is often invoked to relate the experimental data on $B(M1) \propto \left| \langle \psi_f || \mu || \psi_i \rangle \right|^2$ to $B(GT)$ from which $\mathcal{O}(10\,\mathrm{MeV})$ inelastic νA cross sections are estimated [see, e.g., *Langanke et al., Phys. Rev. Lett.* ***93*** *(2004) 202501*]

- What will happen to the $M1$-GT connection when 2B current effects are included?

$M1$ transition in ^{48}Ca: the quenching puzzle

- Large $B(M1 : 0^+ \rightarrow 1^+)$ is expected in ^{48}Ca due to strong $\nu 1f_{7/2} \rightarrow \nu 1f_{5/2}$ excitation

- Darmstadt group's experiments have found a large $B(M1 : 0^+ \rightarrow 1^+)$ but much smaller than expected, suggesting a strong quenching.

- Quenching of $B(GT)$, which is used by traditional nuclear theory to absorb beyond-mean-field and 2B-current contributions to β decay rates, offered as explanation for the strong $B(M1)$ quenching found in Darmstadt group's experiments

- A TUNL experiment at HIγS found a larger value

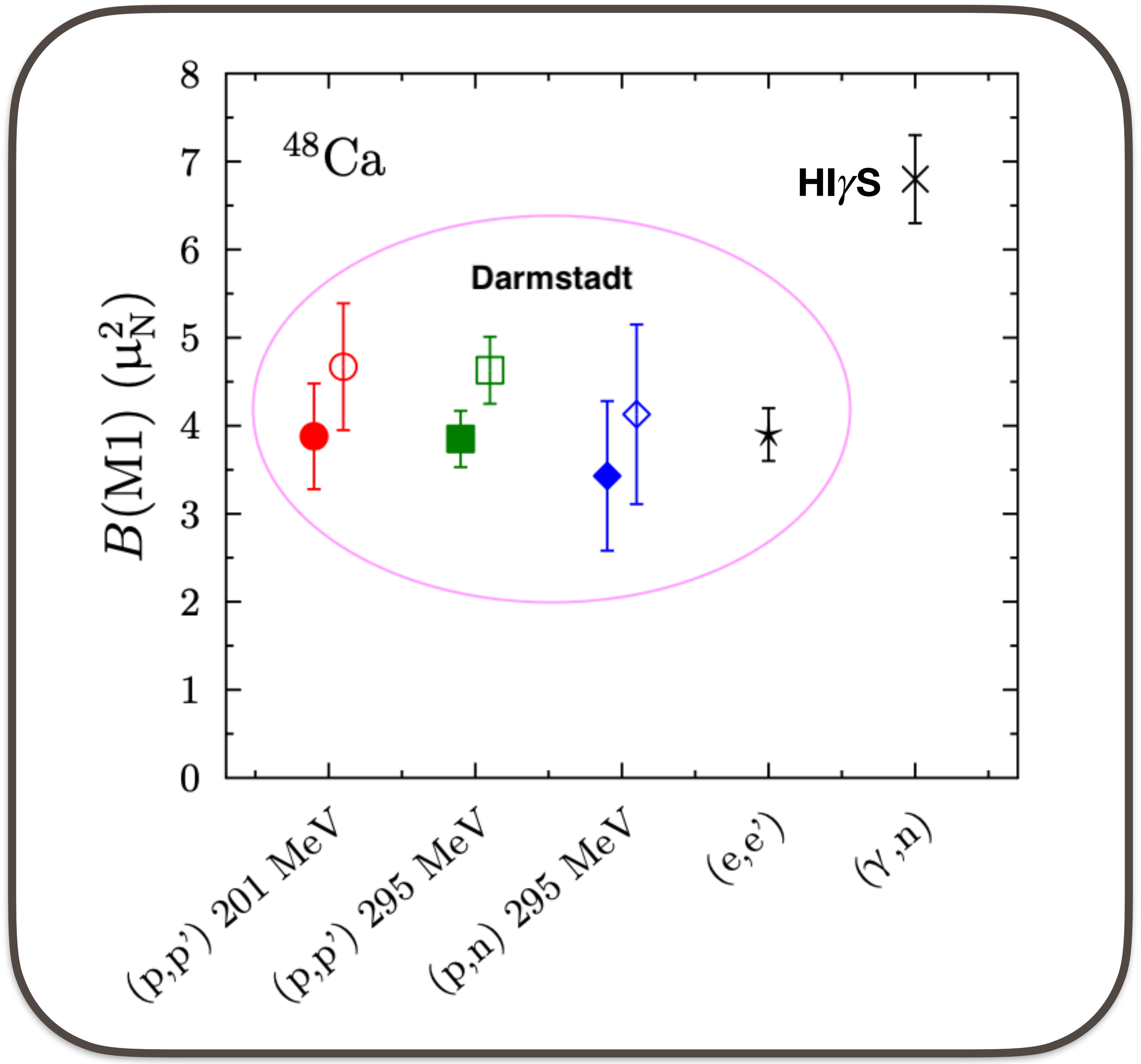
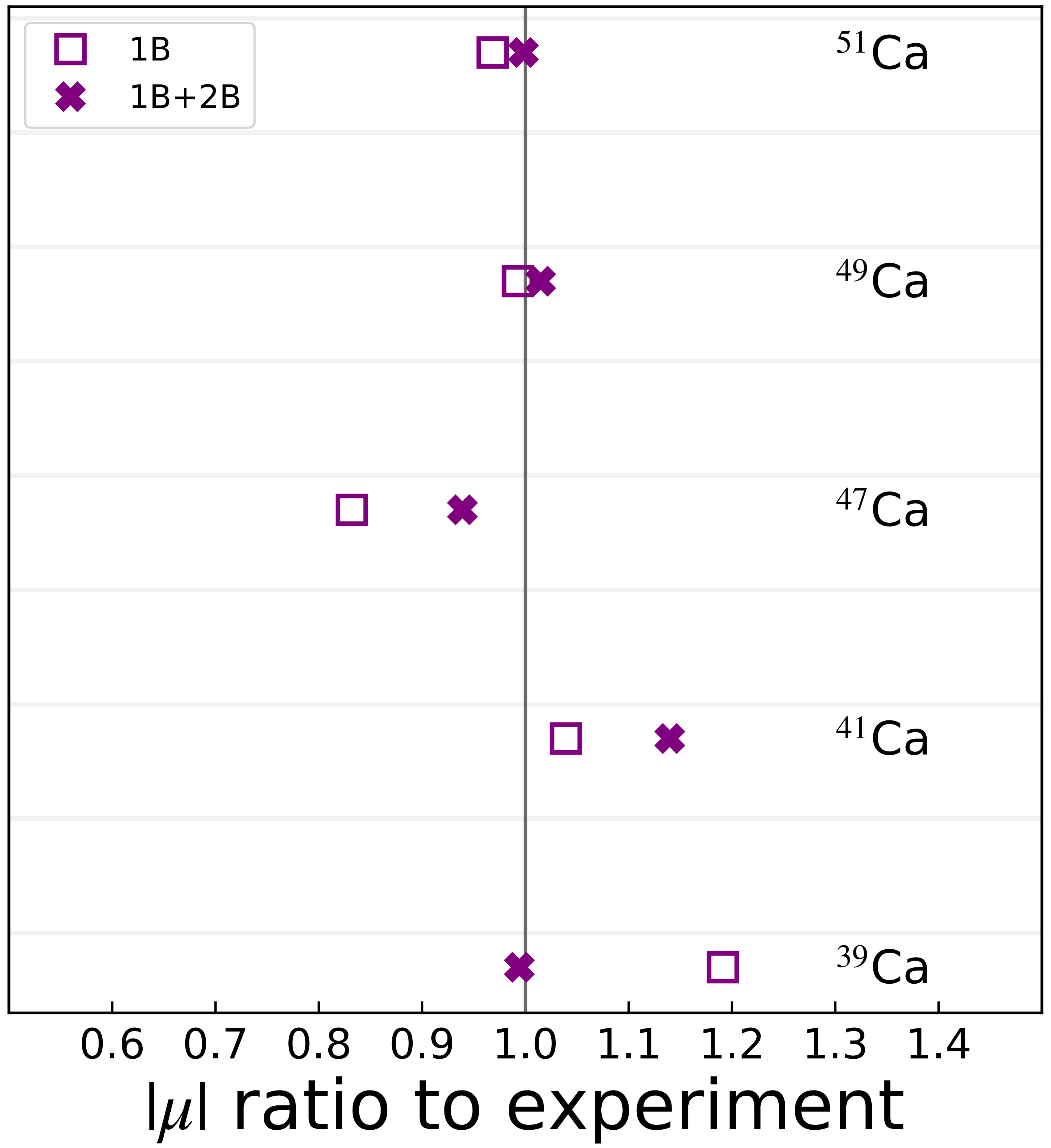
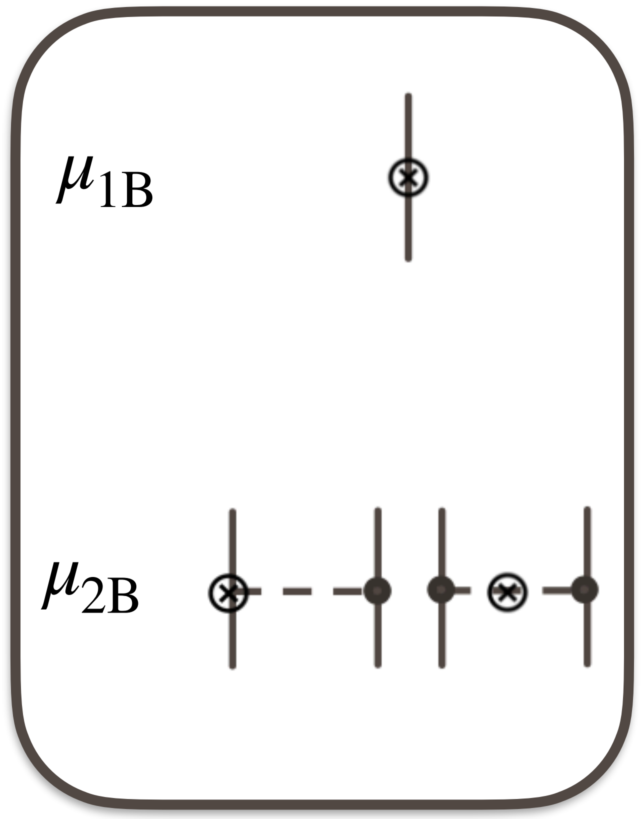


*Figure adapted from PRC **93** (2016) 041302(R)

$M1$ moments in the Ca isotopic chain

BA et al., In preparation

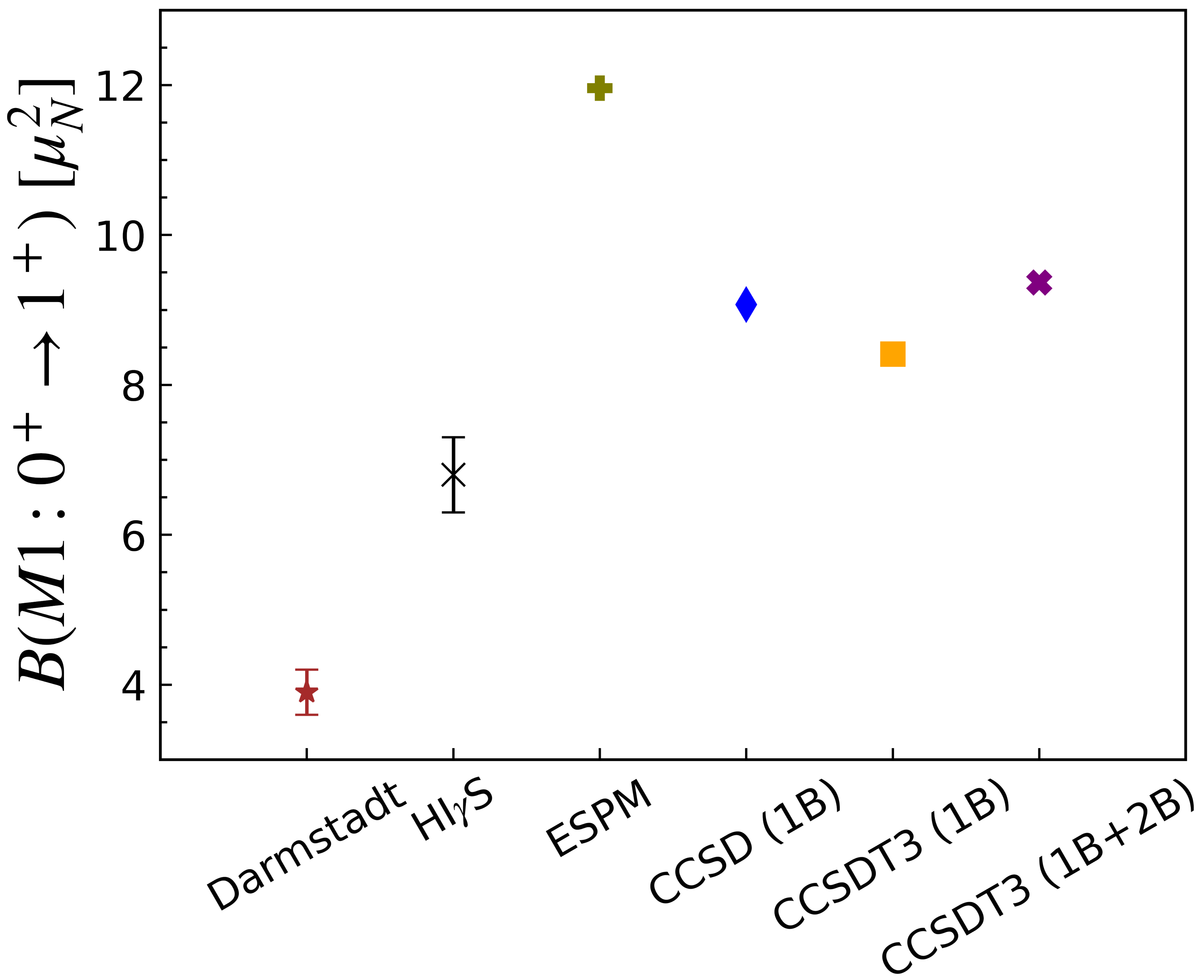




Overall, 2B currents lead to improved description of magnetic moments

$B(M1)$ in $^{48}\mathrm{Ca}$

BA et al., In preparation



Instead of quenching, 2B currents lead to $10\,\%$ enhancement in $B(M1)$!

Conclusions and Outlook

- Accomplished the first *ab initio* computation of longitudinal response in e^- scattering off a medium-mass nucleus

- Theory is closer to TUNL (γ, n) than with Darmstadt (e, e') experiment for $M1$ transition in $^{48}\mathrm{Ca}$; we are working on uncertainty estimates

- Obtained preliminary results for neutrino-nucleus cross sections with 1B currents; inclusion of 2B currents is well underway

Thank you!