TOWARDS *AB INITIO* COMPUTATIONS OF NEUTRINO SCATTERING ON MEDIUM-MASS NUCLEI

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in collaboration with
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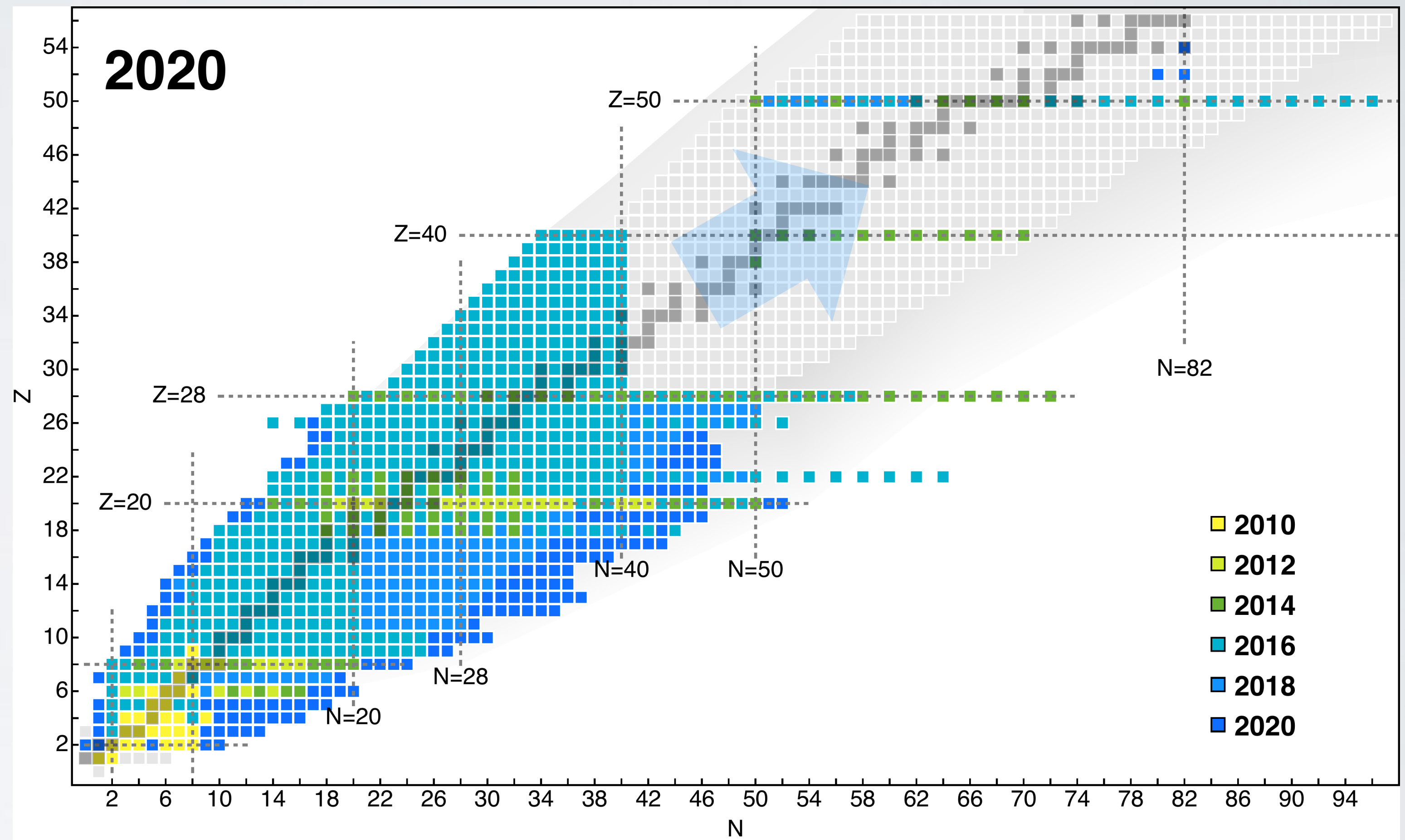
JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Cluster of Excellence
PRiSMA+
Precision Physics, Fundamental Interactions and Structure of Matter

MOTIVATION

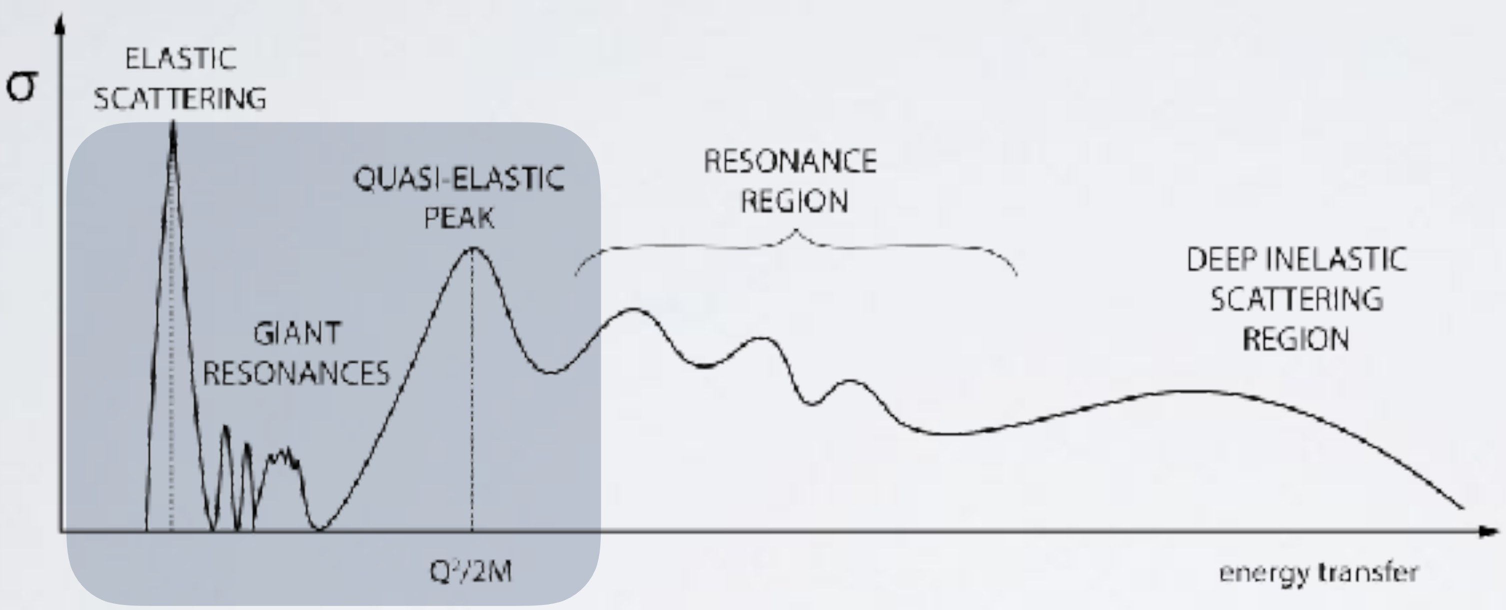
- ✓ Recent developments in many-body nuclear methods
- ✓ Neutrino programs use as targets medium-size nuclei (^{16}O, ^{40}Ar)



H. Hergert, Front.in Phys. 8 (2020) 379

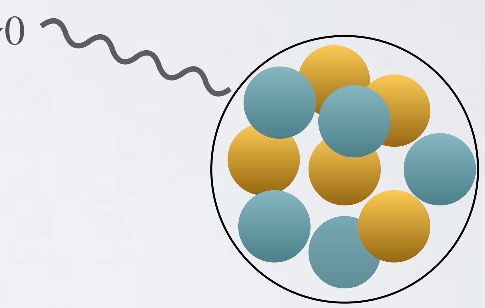
ab initio methods can give more insight into ν-nucleus interaction

NUCLEAR RESPONSE



$$J_\mu = (\rho, \vec{j}) \,|\, \Psi \rangle$$

$\gamma, W^{\pm}, Z^0$



$$\sigma \propto L^{\mu\nu} R_{\mu\nu}$$

lepton tensor

nuclear responses

$$R_{\mu\nu}(\omega, q) = \sum_f \langle \Psi \,|\, J^\dagger_\mu(q) \,|\, \Psi_f \rangle \langle \Psi_f \,|\, J_\nu(q) \,|\, \Psi \rangle \delta(E_0 + \omega - E_f)$$

ELECTRONS FOR NEUTRINOS

$$\left.\frac{d\sigma}{d\omega dq}\right|_{\nu/\bar{\nu}} = \sigma_0\left(v_{CC}R_{CC} + v_{CL}R_{CL} + v_{LL}R_{LL} + v_T R_T \pm v_{T'}R_{T'}\right)$$

$$\left.\frac{d\sigma}{d\omega dq}\right|_{e} = \sigma_M\left(v_L R_L + v_T R_T\right)$$

- ✓ much more precise data
- ✓ we can get access to R_L and R_T separately (Rosenbluth separation)
- ✓ experimental programs of electron scattering in JLab, MAMI, MESA

→ We will start with longitudinal response

AB INITIO NUCLEAR THEORY FOR NEUTRINOS

✓ Nuclear Hamiltonian

$$\mathscr{H}\,|\Psi\rangle = E\,|\Psi\rangle$$

✓ Electroweak currents

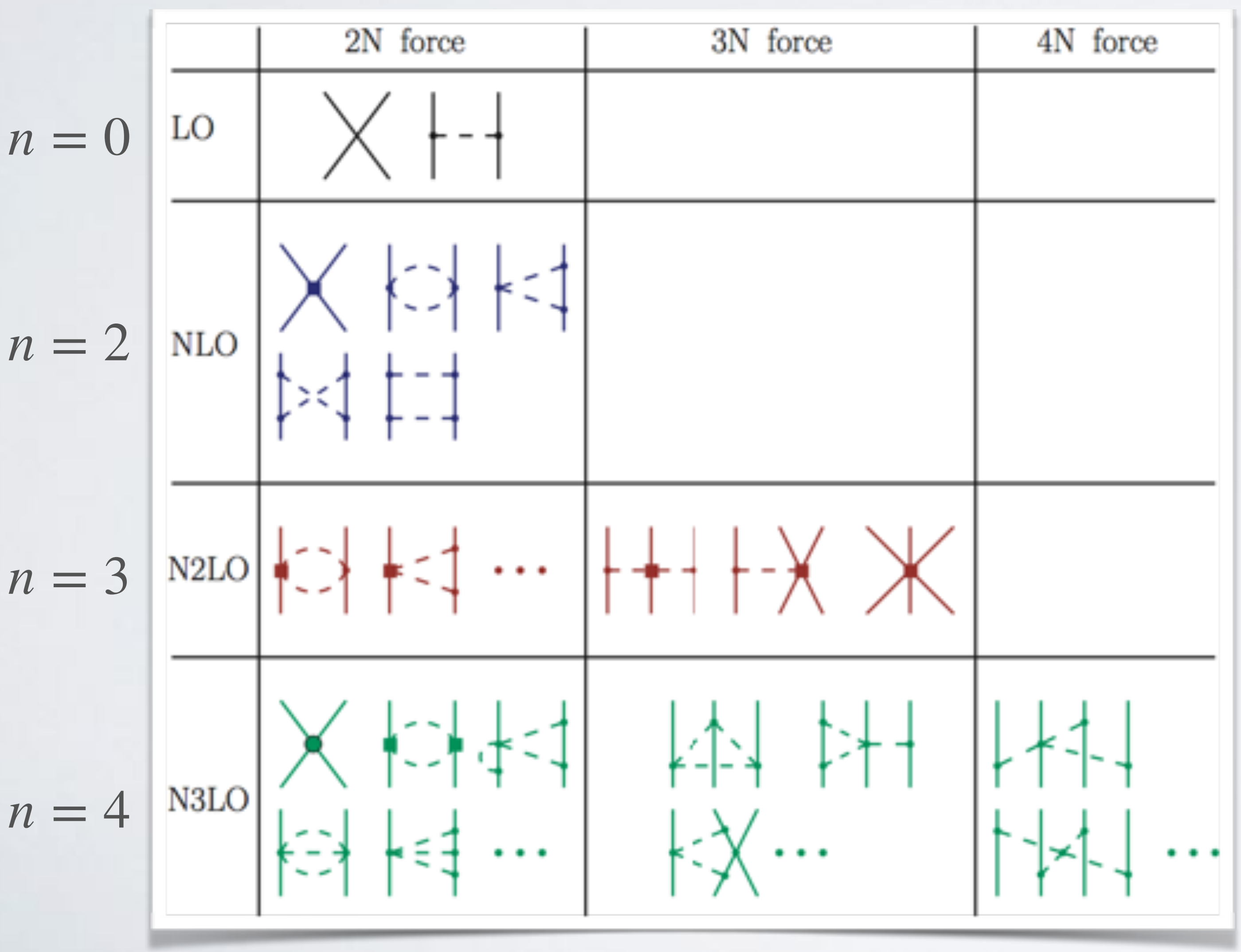
$$J^\mu = (\rho, \vec{j})$$

✓ Many-body method

$$\mathscr{A} = \langle \Psi_m \,|\, J_\mu \,|\, \Psi_n \rangle$$

NUCLEAR HAMILTONIAN

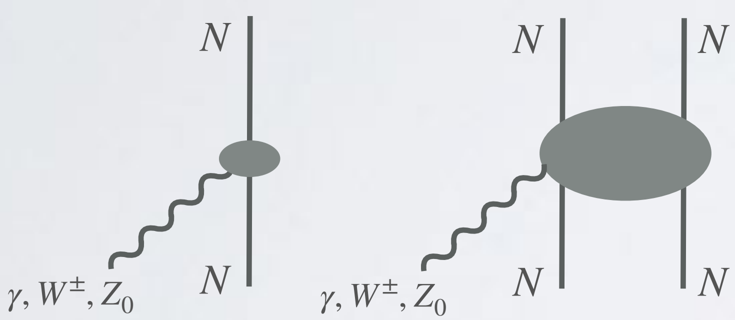
$$\mathcal{H} = \sum_i \frac{p_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$



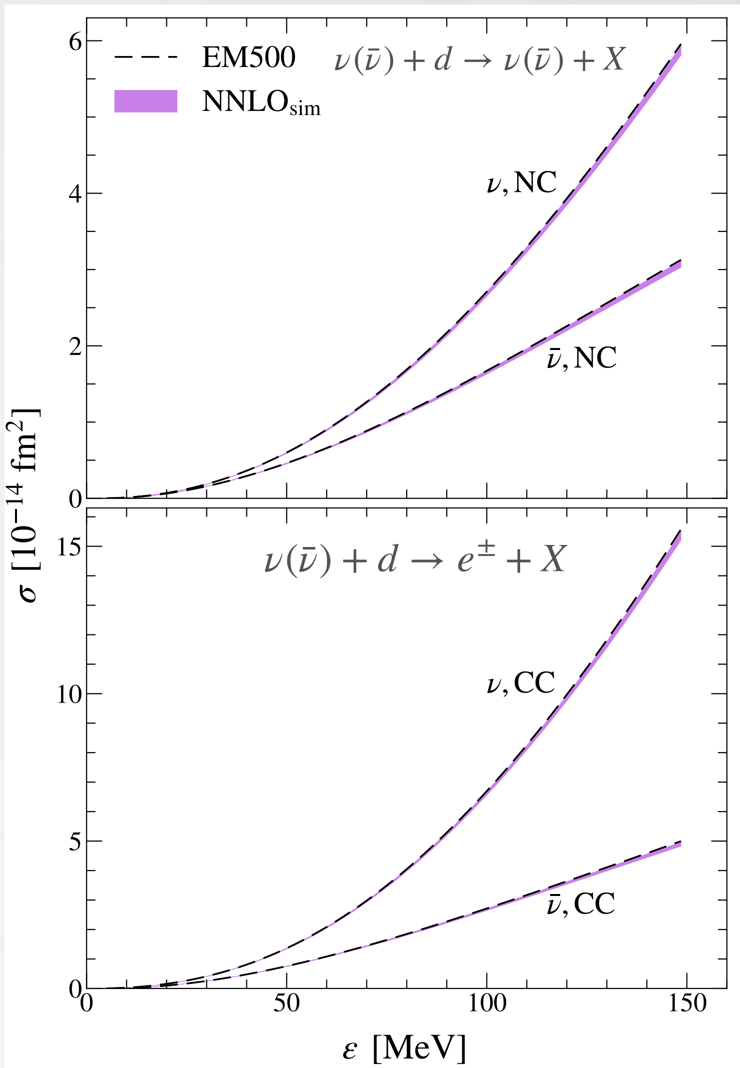
- Chiral Hamiltonians exploiting chiral symmetry (QCD); $\pi, N, (\Delta)$ degrees of freedom
- counting scheme in $\left(\frac{Q}{\Lambda}\right)^n$
- low energy constants (LEC) fit to data
- uncertainty assessment

ELECTROWEAK CURRENTS

$$J = \sum_i j_i + \sum_{i<j} j_{ij} + \dots$$



known to give significant contribution for neutrino-nucleus scattering



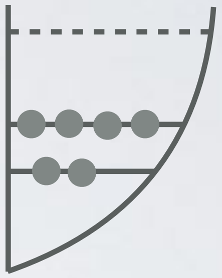
Multipole decomposition for 1- and 2-body EW currents

Current decomposition into multipoles needed for various *ab initio* methods: Coupled Cluster, No Core Shell Model, In-Medium Similarity Renormalization Group

B. Acharya, S. Bacca
Phys.Rev.C 101 (2020) 1, 015505

COUPLED CLUSTER METHOD

Reference state (Hartree-Fock): $|\Psi\rangle$



Include correlations through e^T operator

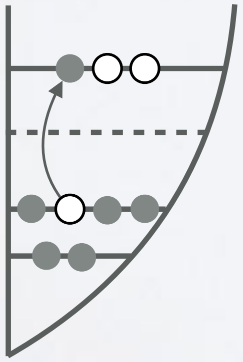
similarity transformed Hamiltonian (non-Hermitian)

$$e^{-T}\mathcal{H}e^{T}|\Psi\rangle \equiv \bar{\mathcal{H}}|\Psi\rangle = E|\Psi\rangle$$

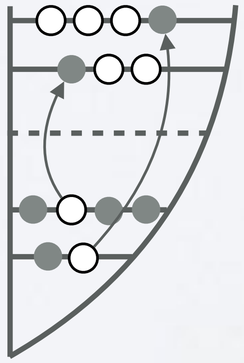
Expansion: $T = \sum t_a^i a_a^\dagger a_i + \sum t_{ab}^{ij} a_a^\dagger a_b^\dagger a_i a_j + \ldots$

←coefficients obtained through coupled cluster equations

singles



doubles



COUPLED CLUSTER METHOD

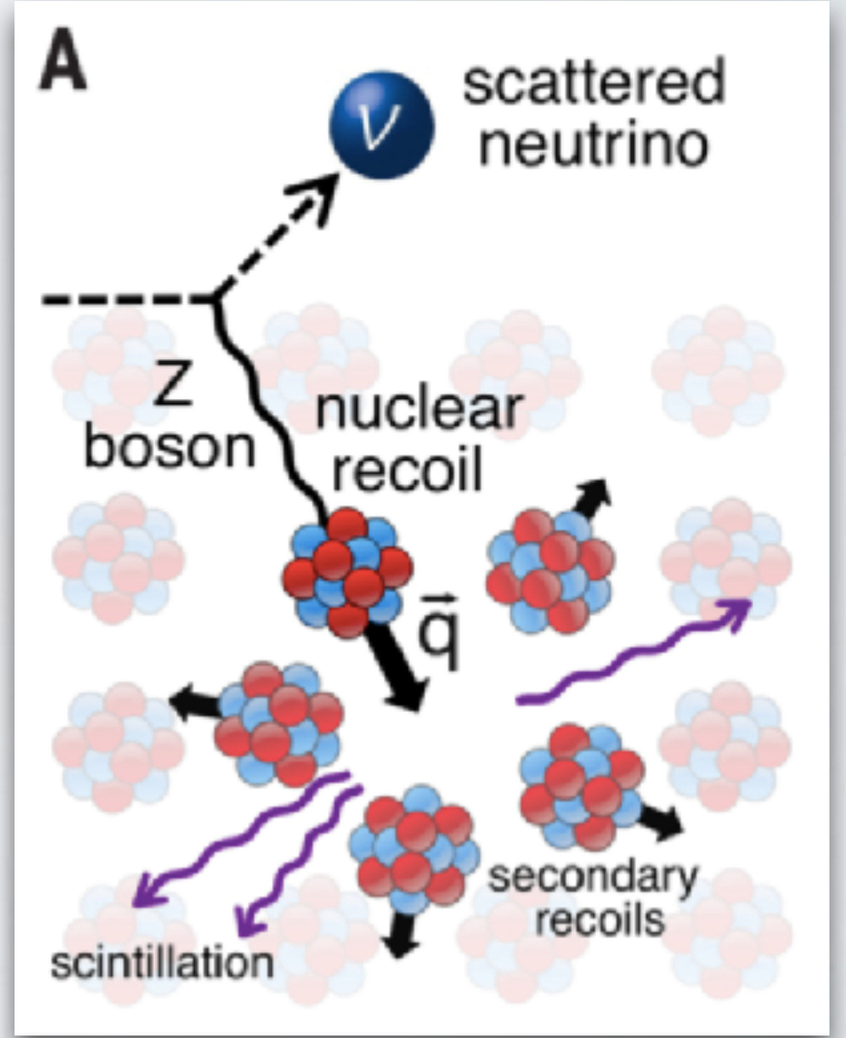
- ✓ Controlled approximation through truncation in T
- ✓ Polynomial scaling with A (predictions for ^{100}Sn)
- ✓ Designed for parallel computing
- ✓ Works most efficiently for doubly magic nuclei

COHERENT ELASTIC ν SCATTERING ON ^{40}Ar

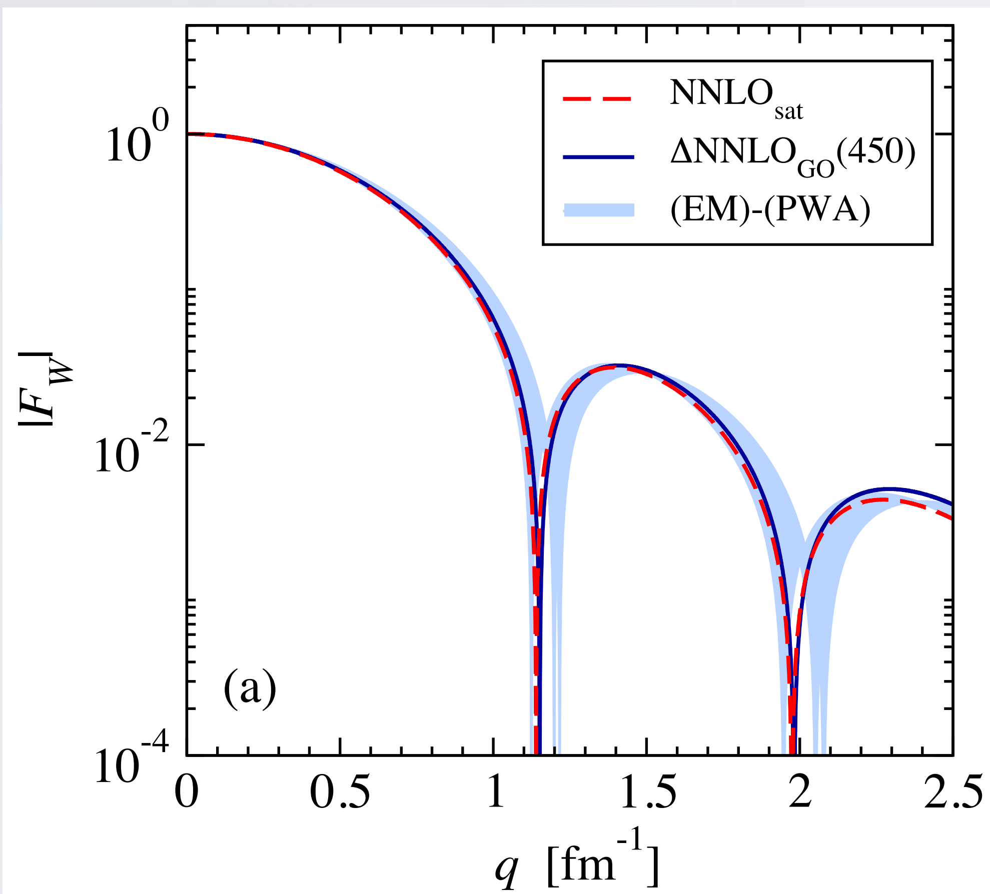
- ✓ No internal excitation of nucleus
- ✓ Nuclear recoil T is measured
- ✓ up to $E_\nu \simeq 50$ MeV

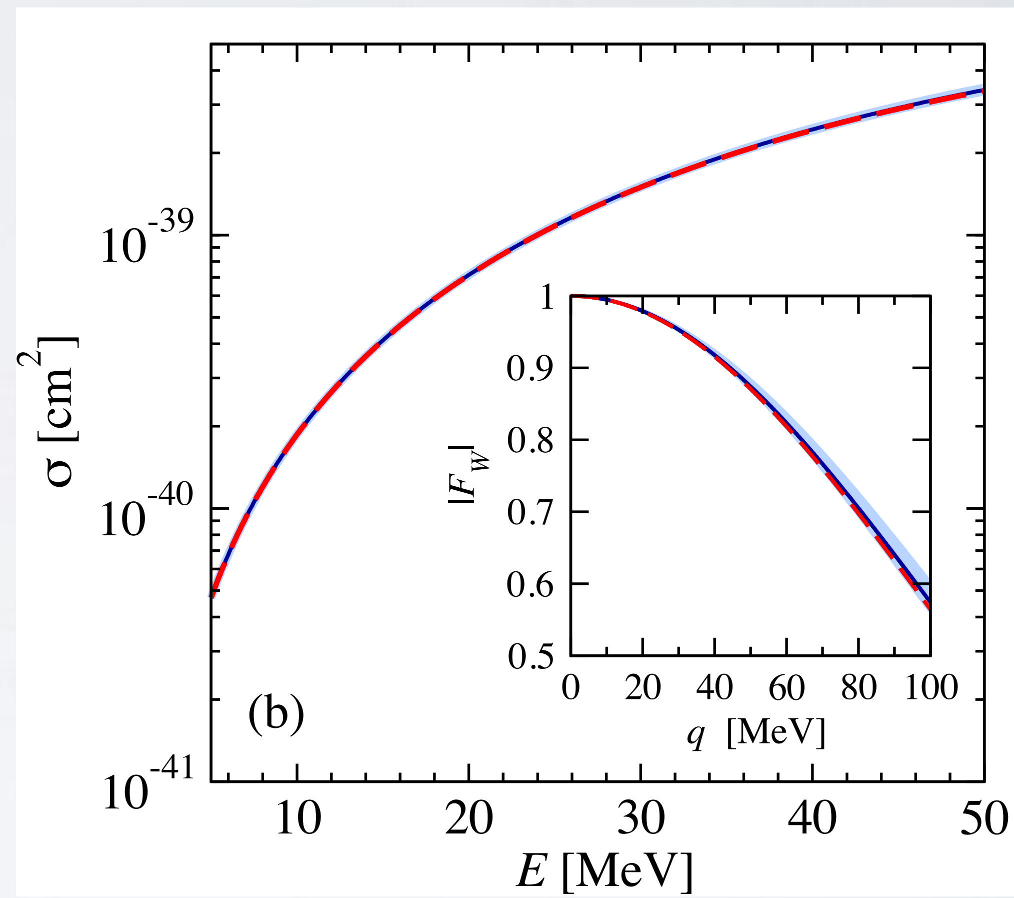
$$\frac{d\sigma}{dT}(E_\nu, T) \simeq \frac{G_F^2}{4\pi} M \left[1 - \frac{MT}{2E_\nu^2}\right] Q_W^2 F_W^2(q^2) \propto N^2$$

$$F_W(q^2) = \frac{1}{Q_W}\left[N F_n(q^2) - (1 - 4\sin^2\theta_W) Z F_p(q^2)\right]$$



COHERENT ELASTIC ν SCATTERING ON ^{40}Ar

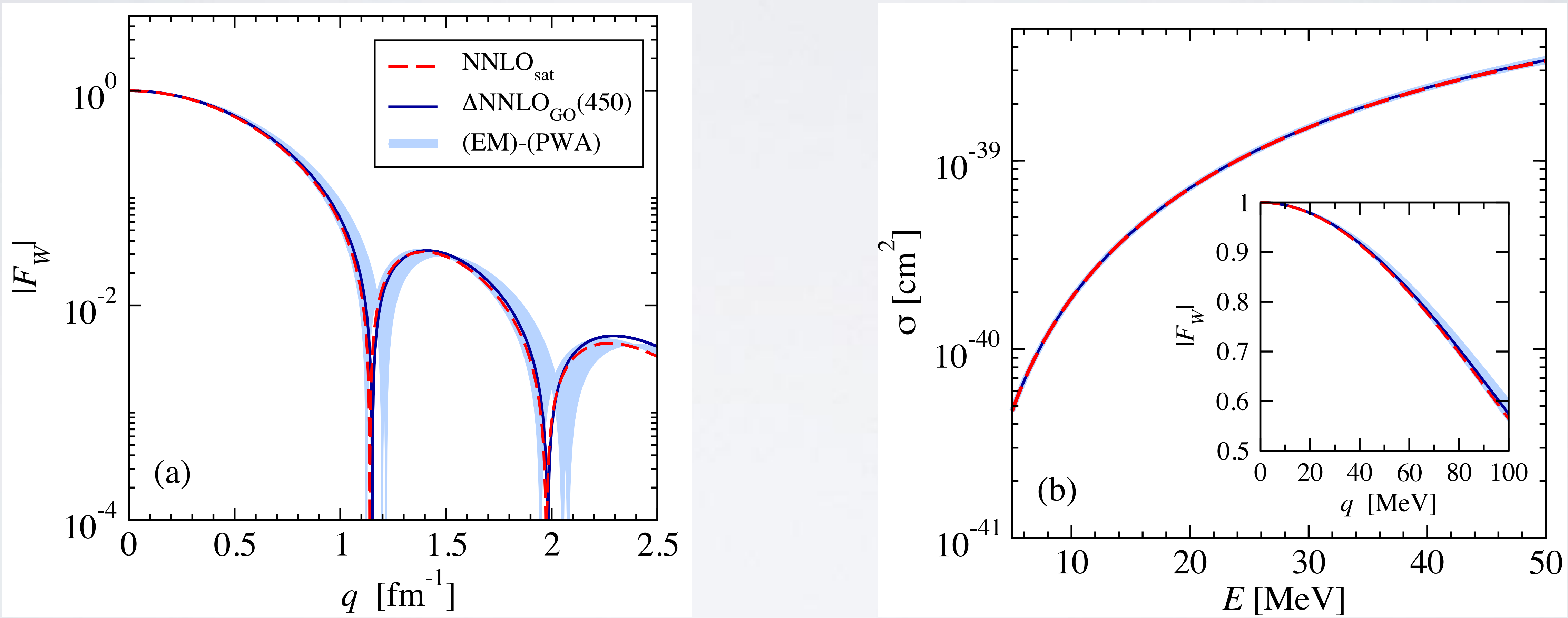




small nuclear structure uncertainties

C. Payne at al.
Phys.Rev.C 100 (2019) 6, 061304

COHERENT ELASTIC ν SCATTERING ON ^{40}Ar



These results based on the properties of ground-state. For nuclear responses we need excited states.

small nuclear structure uncertainties

C. Payne at al.
Phys.Rev.C 100 (2019) 6, 061304

LORENTZ INTEGRAL TRANSFORM

$$R_{\mu\nu}(\omega, q) = \sum\!\!\!\!\!\!\int_f \langle \Psi | J_\mu^\dagger | \Psi_f \rangle \langle \Psi_f | J_\nu | \Psi \rangle \delta(E_0 + \omega - E_f)$$

continuum spectrum

Instead we calculate

$$S_{\mu\nu}(\omega, q) = \int d\sigma K(\omega, \sigma) R_{\mu\nu}(\sigma, q) = \langle \Psi | J_\mu^\dagger \; K(\omega, \mathscr{H} - E_0) \; J_\nu | \Psi \rangle$$

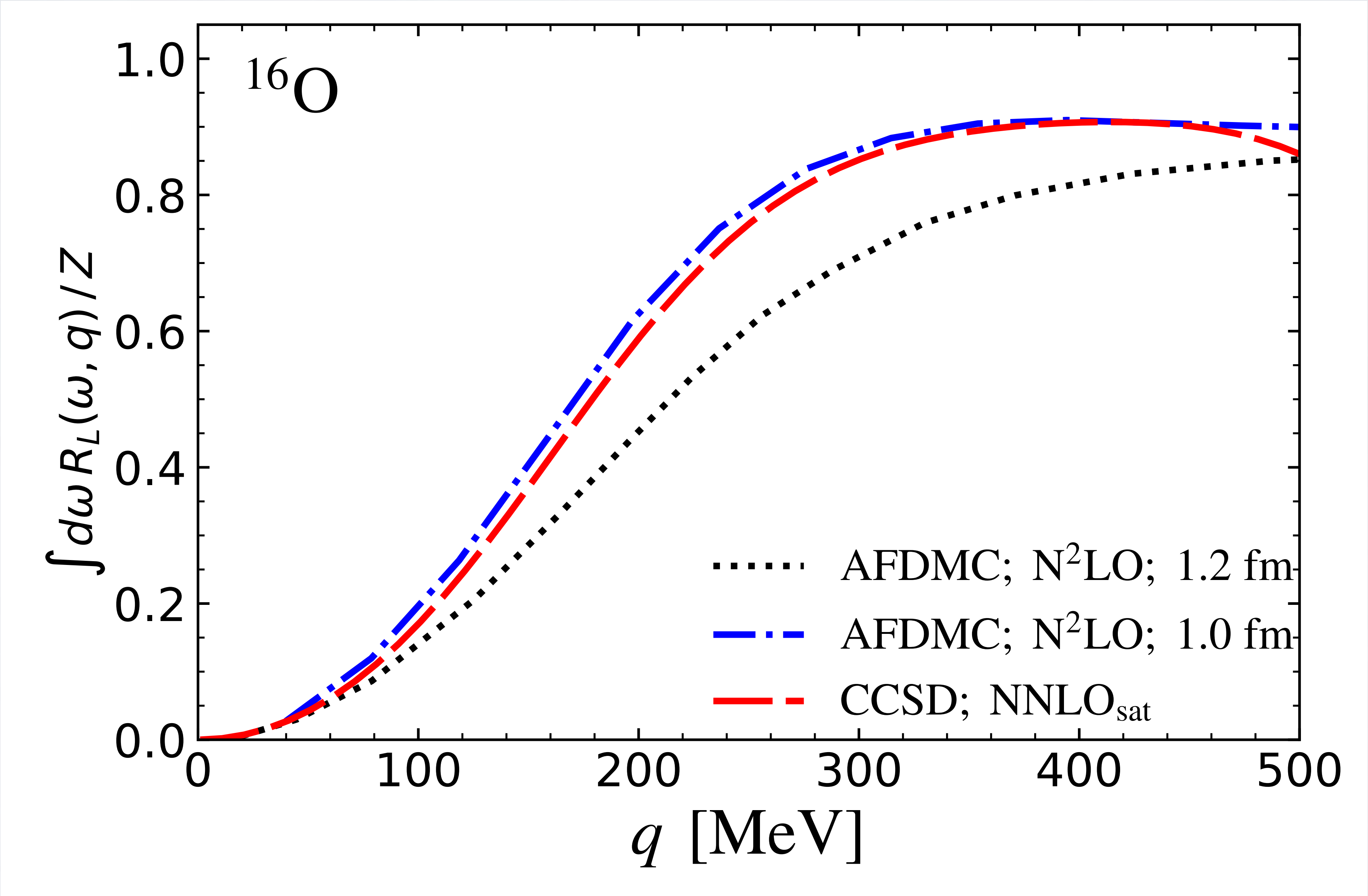
$S_{\mu\nu}$ has to be inverted to get access to $R_{\mu\nu}$

Lorentzian kernel:

$$K_\Lambda(\omega, \sigma) = \frac{1}{\pi} \frac{\Lambda}{\Lambda^2 + (\omega - \sigma)^2}$$

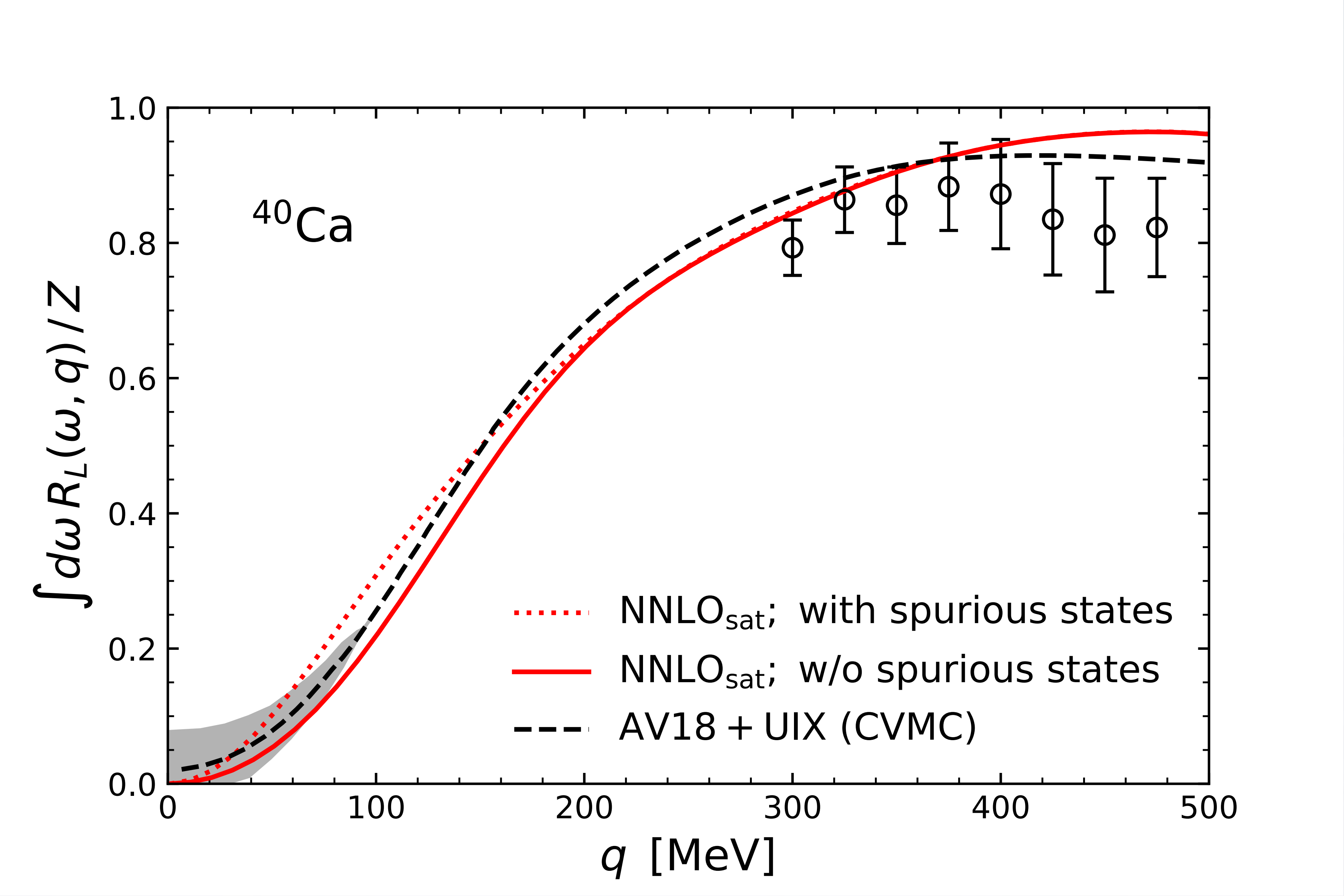
➡ LIT-CC used for photo-absorption

COULOMB SUM RULE



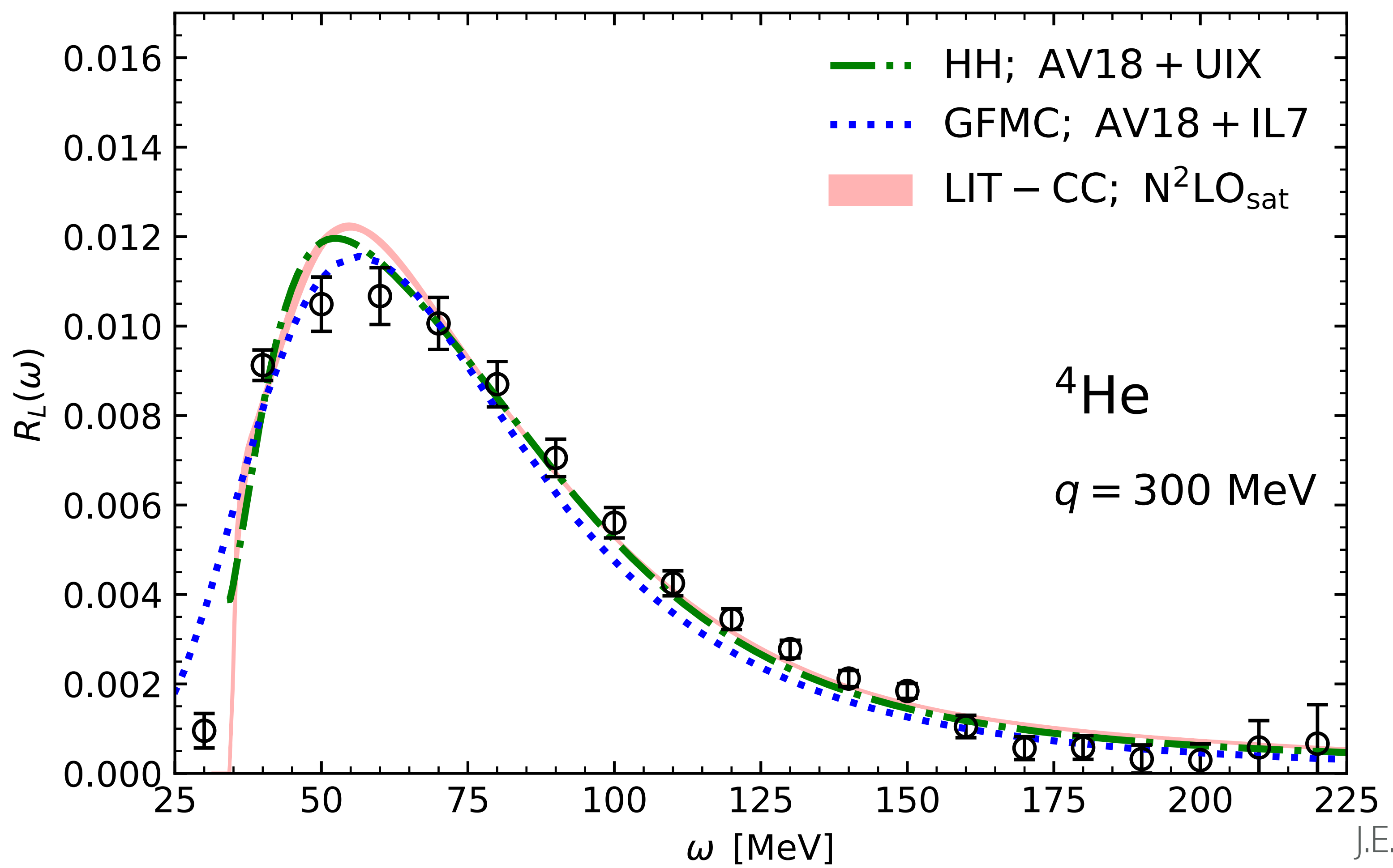
J.E.S. B. Acharya, S.Bacca, G. Hagen
Phys.Rev.C 102 (2020) 064312

COULOMB SUM RULE



J.E.S. et al.
arXiv: 2103.06786

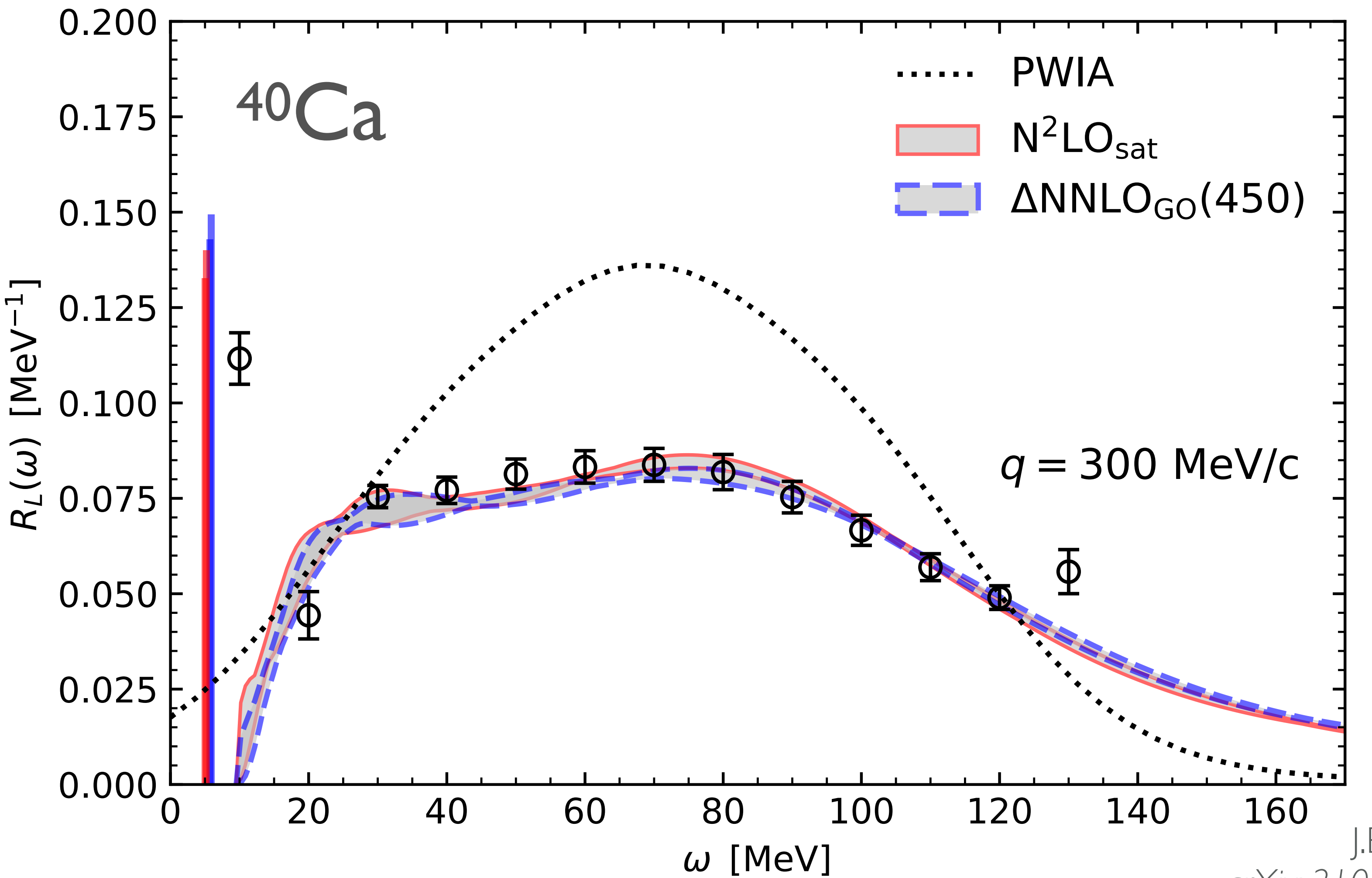
LONGITUDINAL RESPONSE



J.E.S. et al.
arXiv: 2103.06786

Uncertainty band: inversion procedure

LONGITUDINAL RESPONSE



J.E.S. et al.
arXiv: 2103.06786

- Results for 2 different chiral potentials
- Comparison with Plane wave impulse approximation (PWIA)

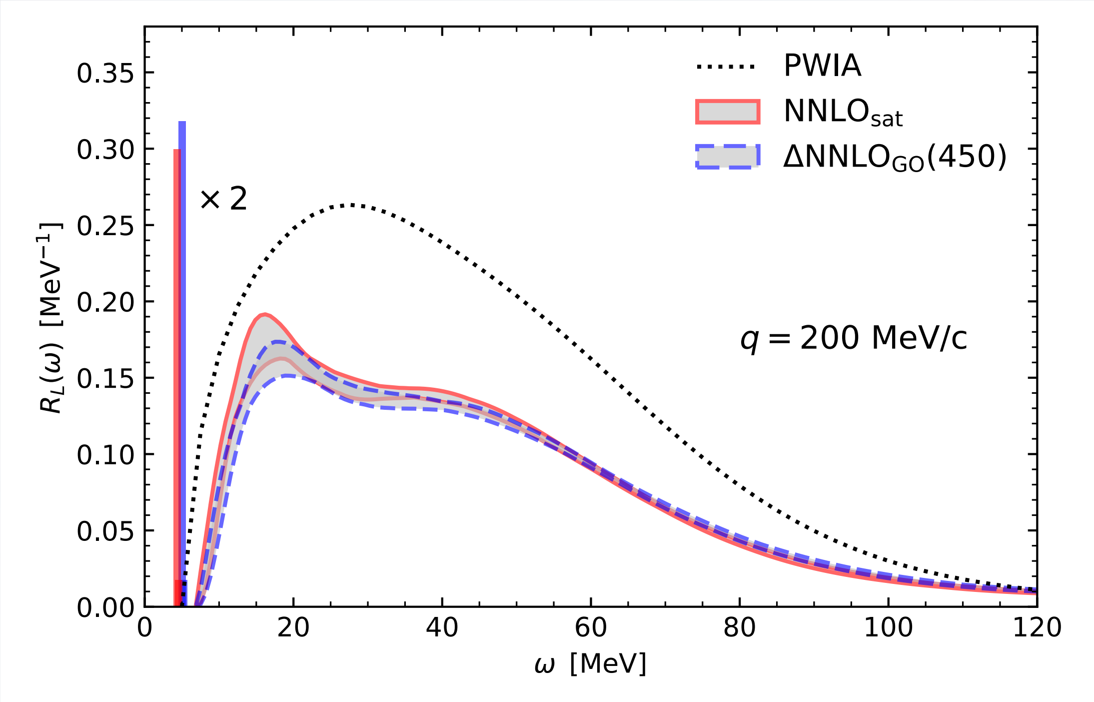
OUTLOOK & CONCLUSIONS

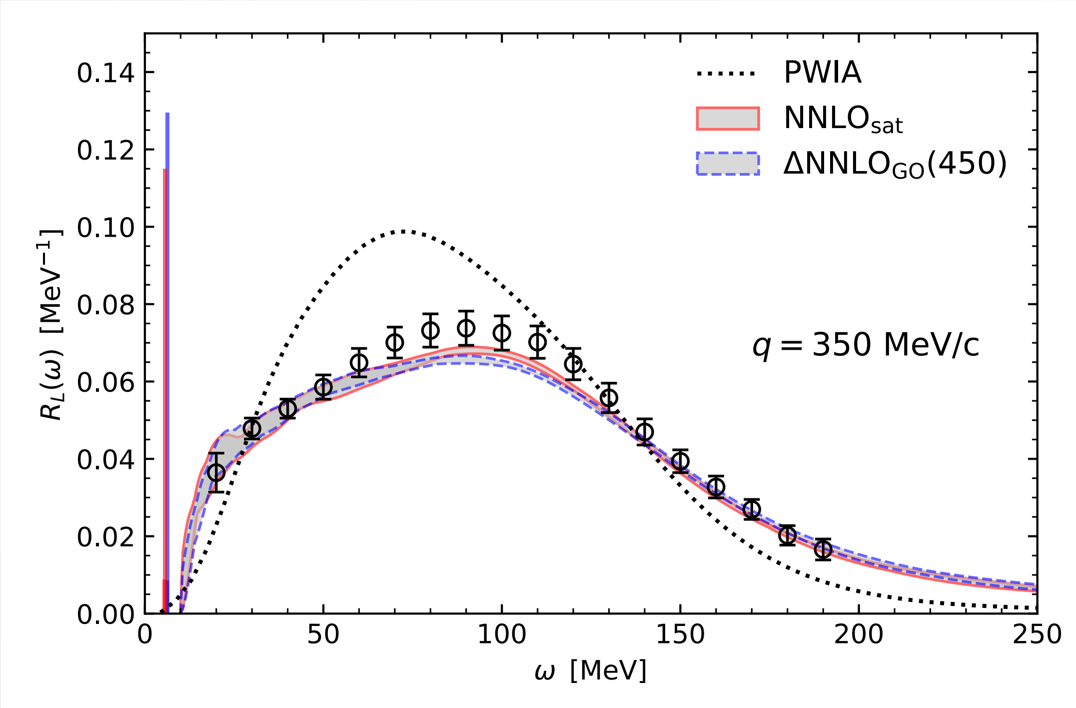
- Nuclear physics is challenged by neutrino oscillation experiments
- We set stage for neutrino-nucleus cross-section calculation
- With LIT-CC we obtained first ab initio results for longitudinal response for medium-size nuclei (^{16}O and ^{40}Ar can be addressed)
- Next step: transverse response $\left.\frac{d\sigma}{d\omega dq}\right|_e = \sigma_M\left(v_L R_L + v_T R_T\right)$
- Compute spectral function consistently with CC

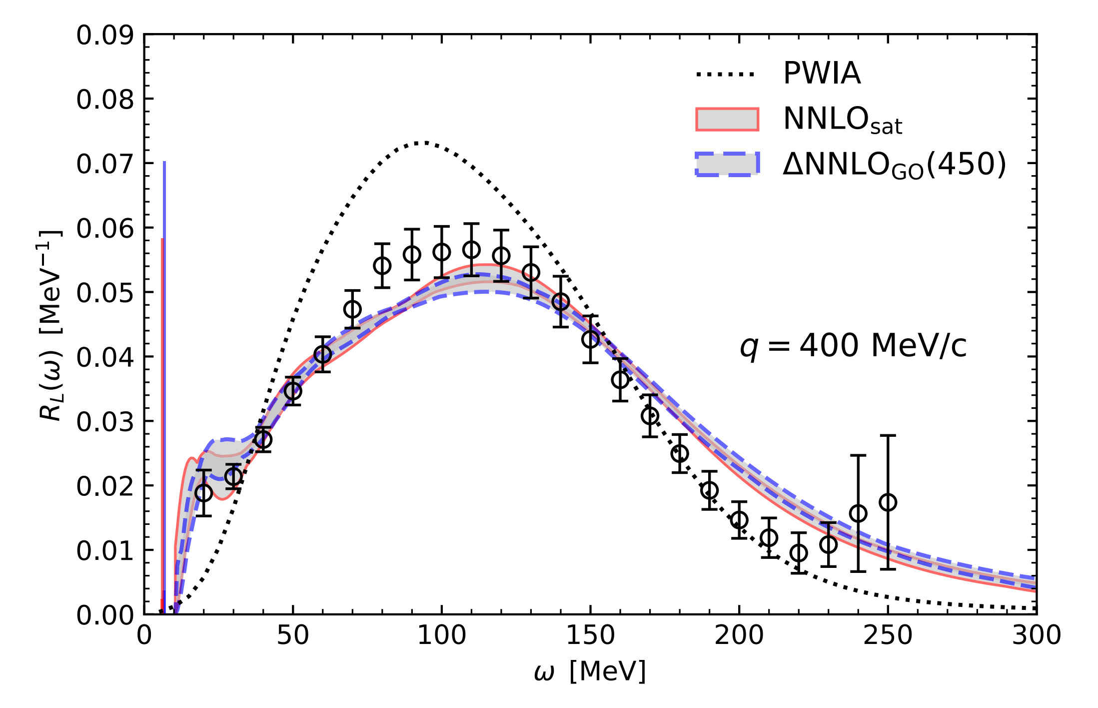
THANK YOU

BACK UP

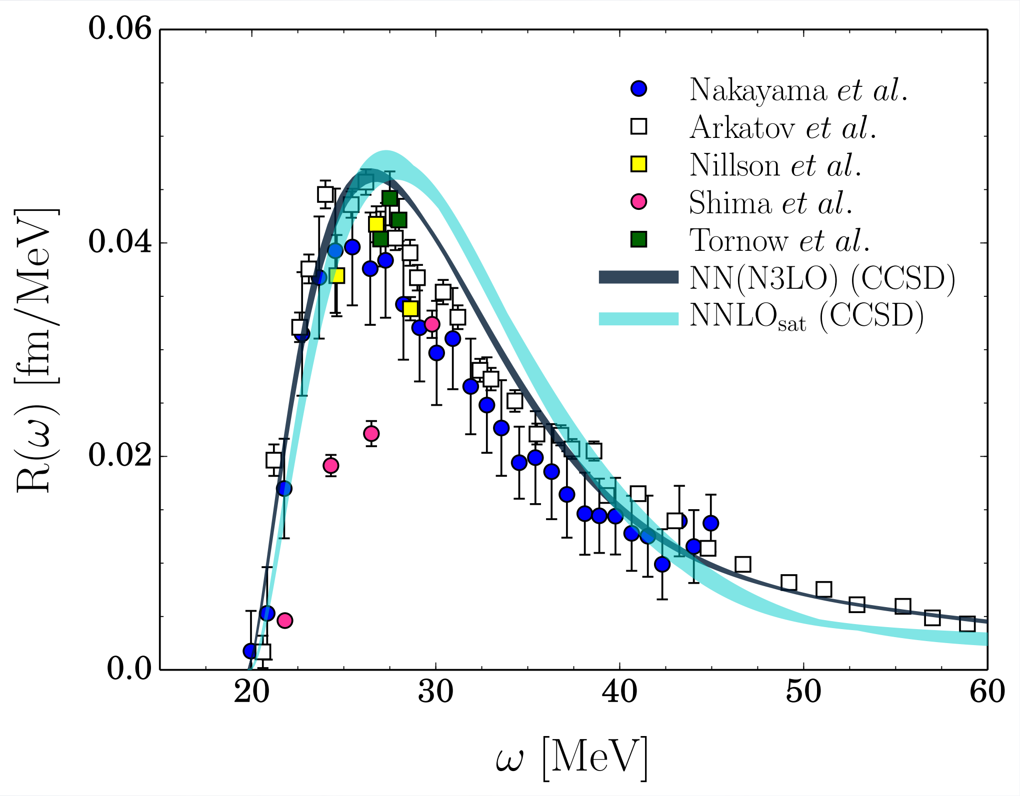
LONGITUDINAL RESPONSE





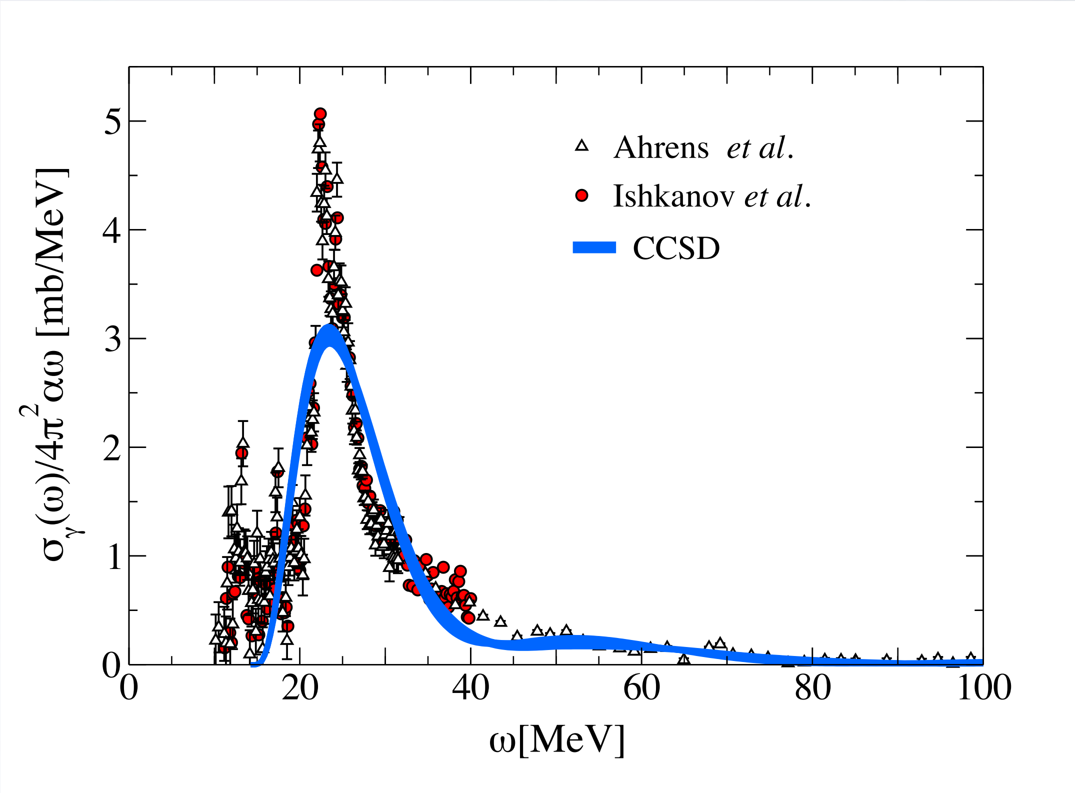


LIT-CC METHOD



M. Miorelli et al.
Phys.Rev.C 94 (2016) 3, 034317

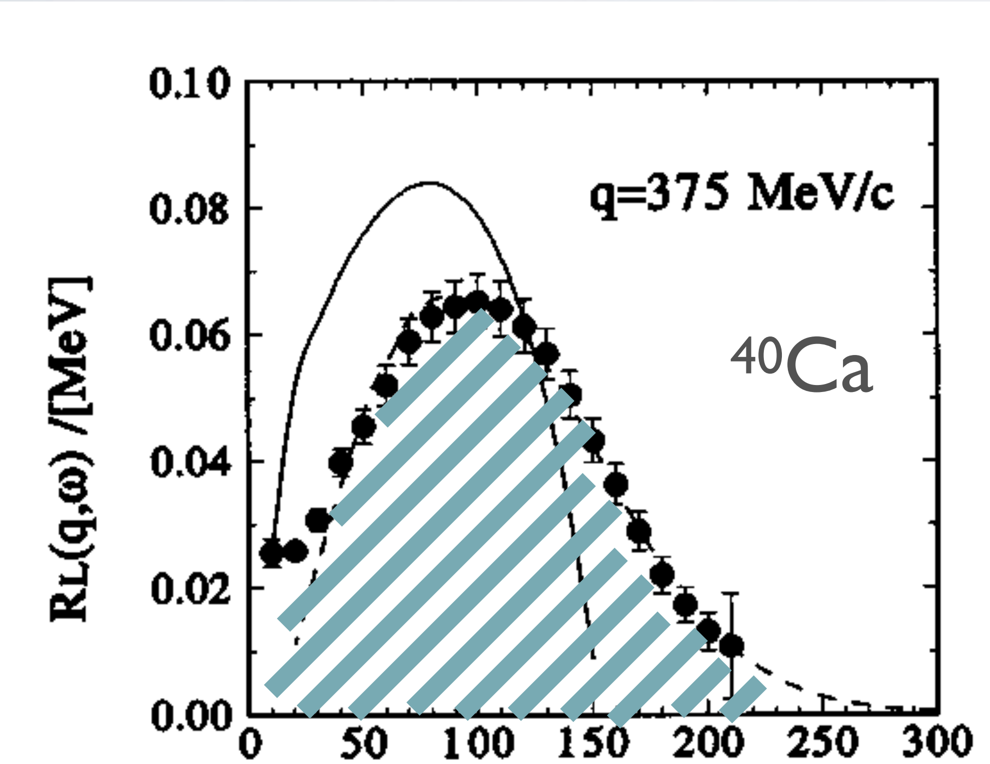
^{4}He photo-absorption



S. Bacca et al.
Phys.Rev.C 90 (2014) 6, 064619

giant dipole resonance in ^{16}O

LONGITUDINAL RESPONSE AND COULOMB SUM RULE



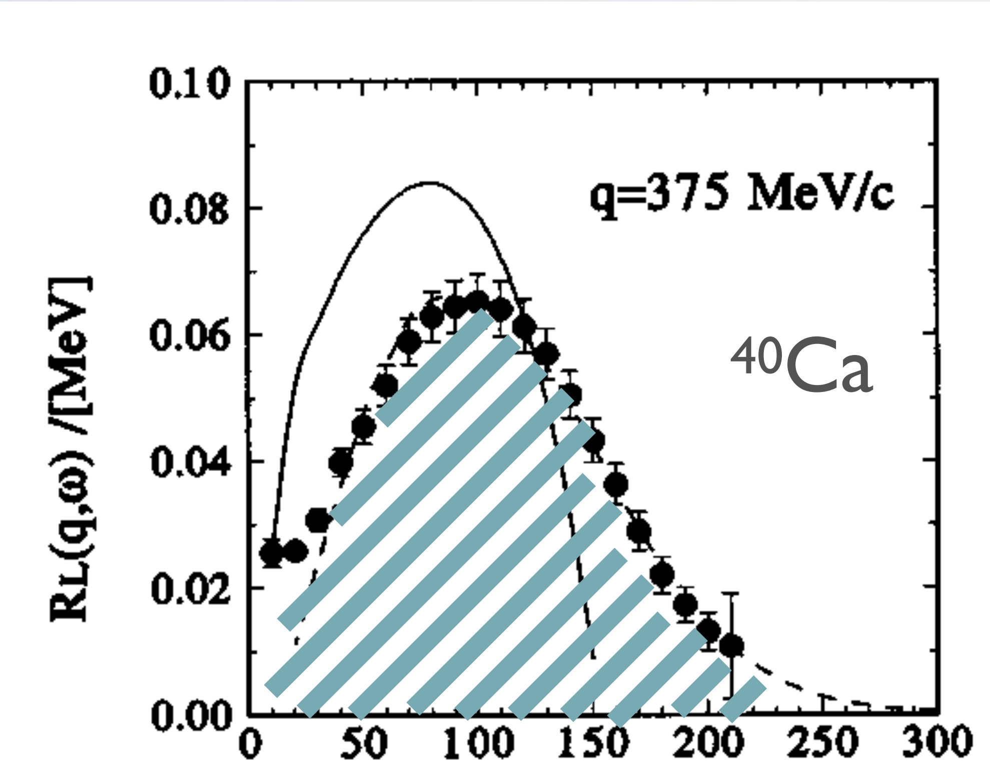
C. F. Williamson et al.
Phys.Rev.C 56, 3152-3172 (1997)

$$R_L(\omega, q) = \sum_f \langle \Psi | \hat{\rho}^\dagger(q) | \Psi_f \rangle \langle \Psi_f | \hat{\rho}(q) | \Psi \rangle \delta(E_0 + \omega - E_f)$$

charge operator $\hat{\rho}(q) = \sum_{j=1}^{Z} e^{iqz'_j}$

- ➡ operator multipole decomposition (and sum)
- ➡ higher energy-momentum transfer than considered earlier
- ➡ translationally non-invariant operator

LONGITUDINAL RESPONSE AND COULOMB SUM RULE



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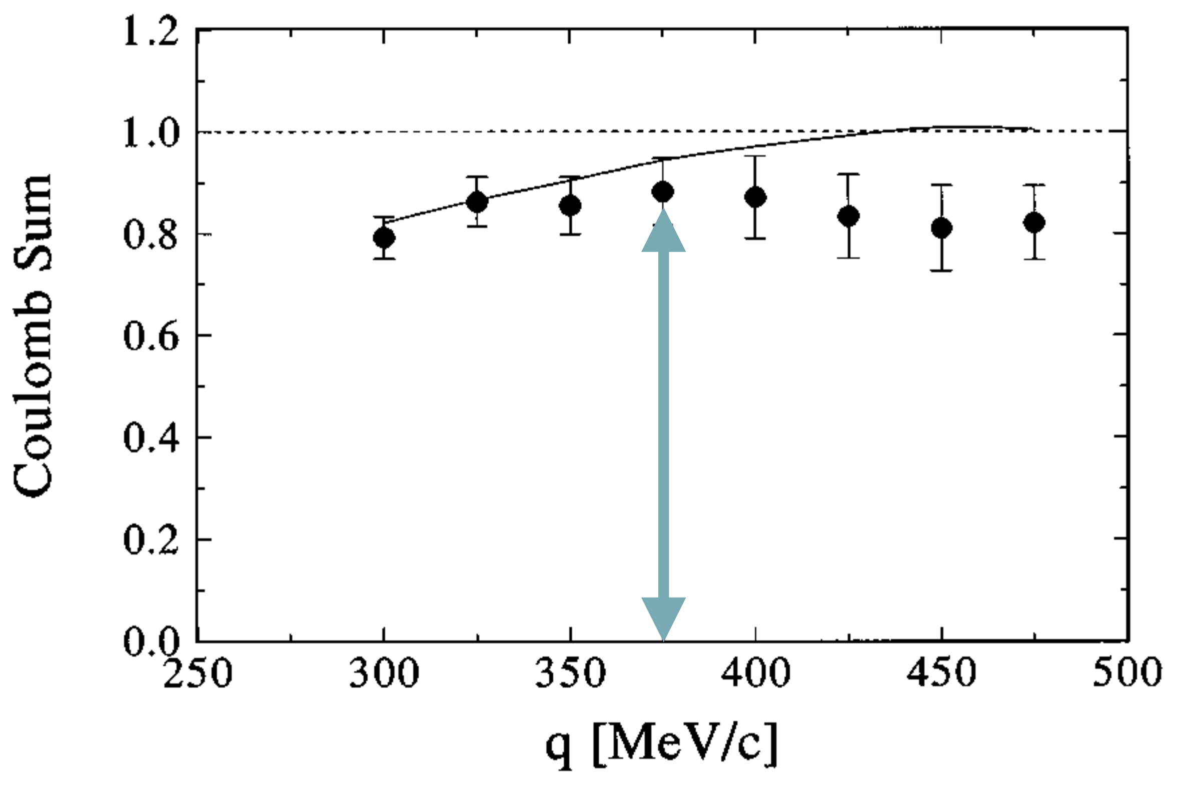


$$R_L(\omega, q) = \sum_f \langle \Psi | \hat{\rho}^\dagger(q) | \Psi_f \rangle \langle \Psi_f | \hat{\rho}(q) | \Psi \rangle \delta(E_0 + \omega - E_f)$$

$$m_0(q) = \int d\omega R_L(\omega, q) = \sum_{f \neq 0} | \langle \Psi_f | \hat{\rho} | \Psi \rangle |^2$$

COULOMB SUM RULE

$$m_0(q) = \int d\omega R_L(\omega, q) = \sum_{f \neq 0} |\langle \Psi_f | \hat{\rho} | \Psi \rangle|^2 = \langle \Psi | \hat{\rho}^\dagger \hat{\rho} | \Psi \rangle - |F_{el}(q)|^2$$

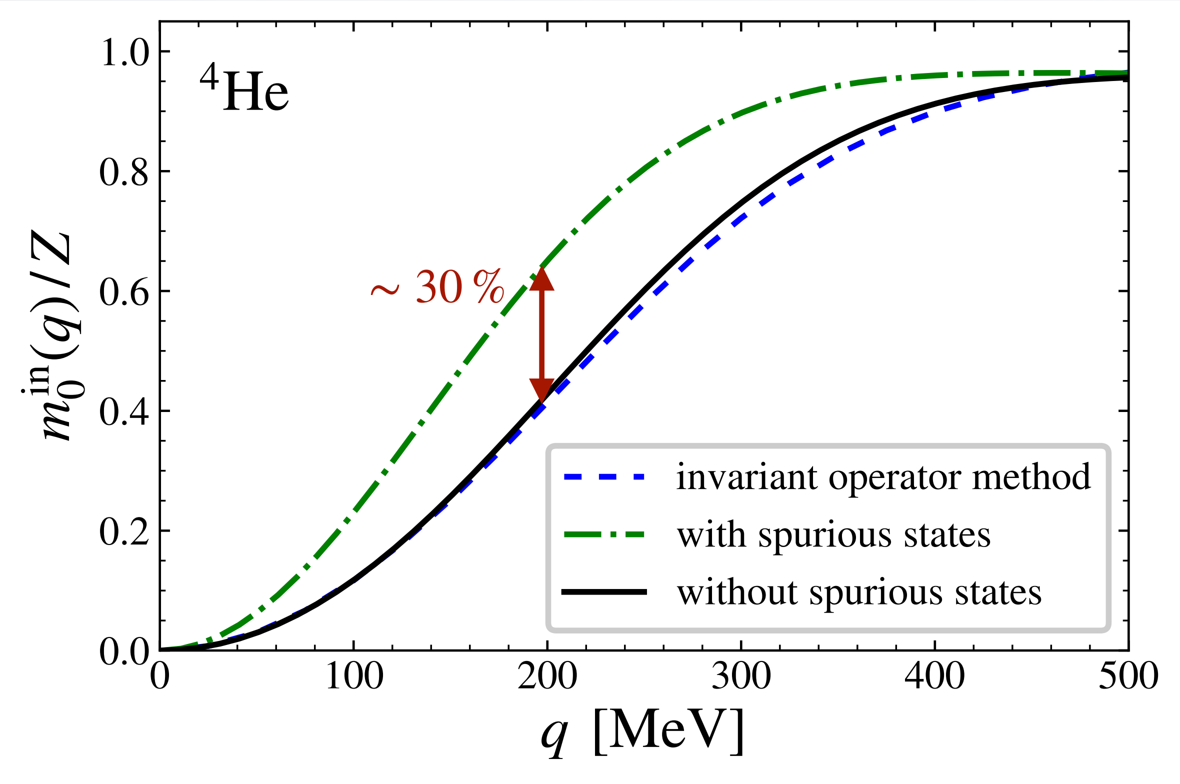
easier to calculate since we do not need $|\Psi_f\rangle$

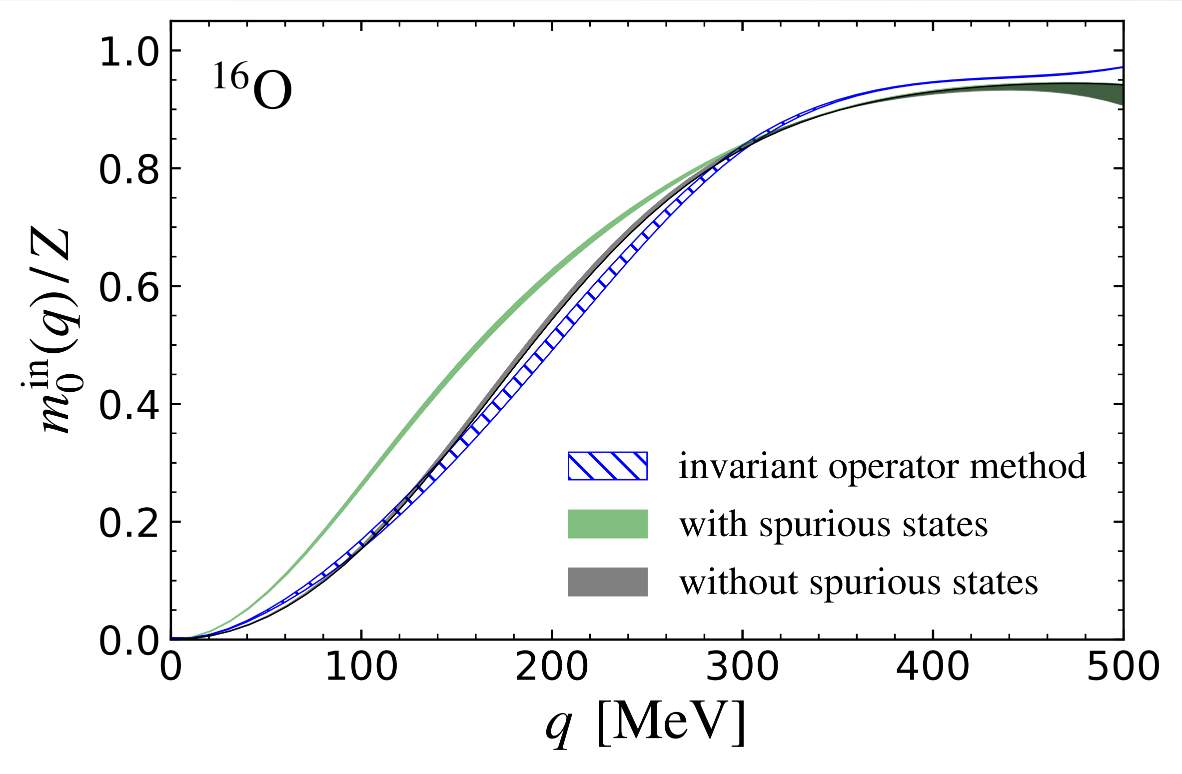
center of mass problem

$|\Psi\rangle$ has 3A coordinates → 3(A-1) intrinsic coordinates + $\vec{R} = \frac{1}{A}\sum_i^A \vec{r}_i$

With translationally non-invariant operators we may excite spurious states

COULOMB SUM RULE





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CoM spurious states dominate for light nuclei

COULOMB SUM RULE

Project out spurious states: $\hat{\rho}\,|\Psi\rangle = |\Psi_{phys}\rangle + |\Psi_{spur}\rangle$

It has been shown that to good approximation the ground state factorizes:

$$|\Psi\rangle = |\Psi_I\rangle\,|\Psi_{CoM}\rangle$$

center of mass wave function is a Gaussian

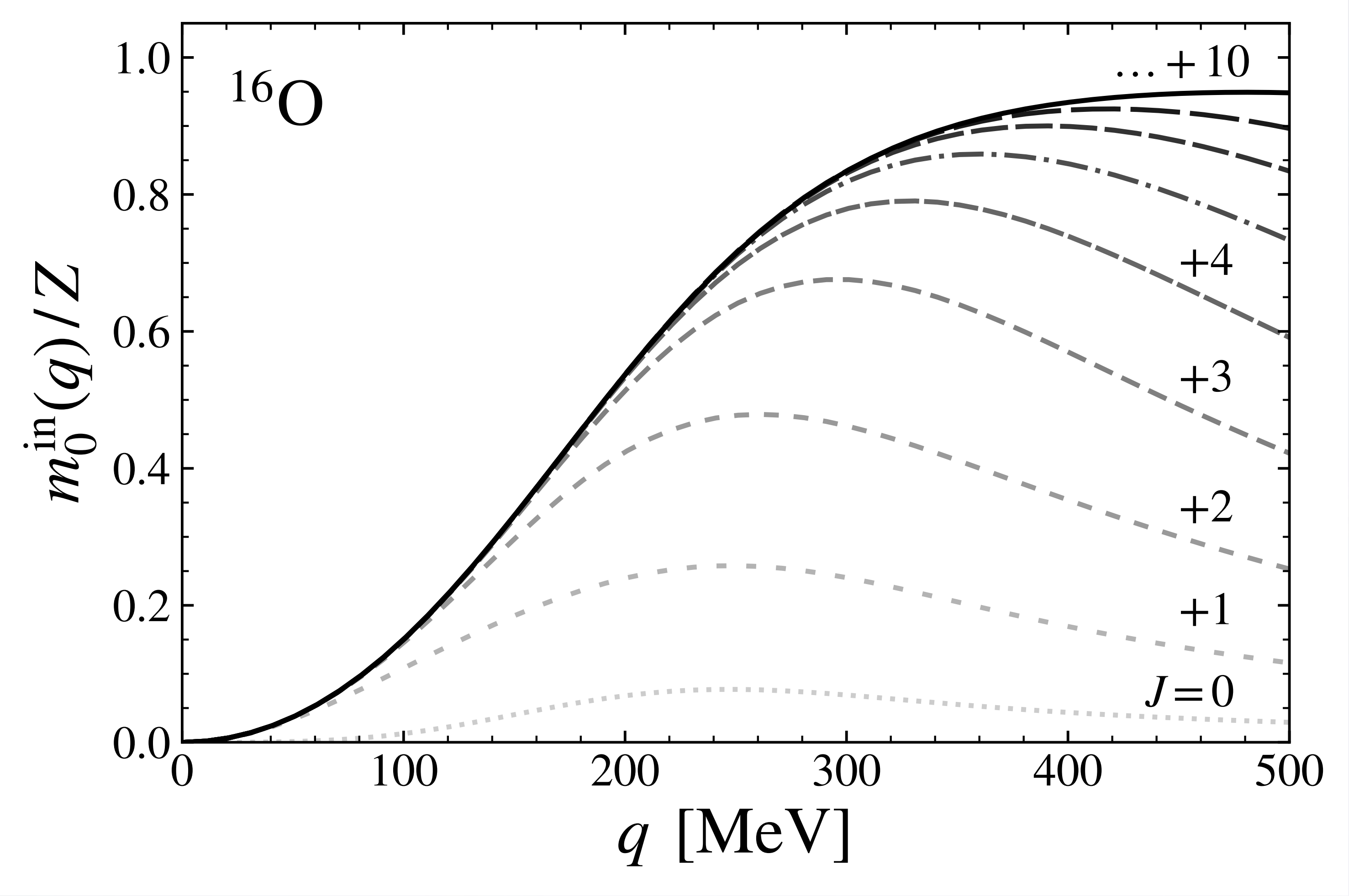
G. Hagen, T. Papenbrock, D. Dean *Phys.Rev.Lett.* 103 (2009) 062503

We follow a similar ansatz for the excited states:

$$\hat{\rho}\,|\Psi\rangle = |\Psi_I^{exc}\rangle\,|\Psi_{CoM}\rangle + \cancel{|\Psi_I\rangle\,|\Psi_{CoM}^{exc}\rangle}$$

spurious

COULOMB SUM RULE



Multipole sum

$$\hat{\rho} = \sum_{J=0}^{\infty} [\hat{\rho}]^J$$