Electromagnetic response and pion-nucleus scattering with ab initio nuclear structure

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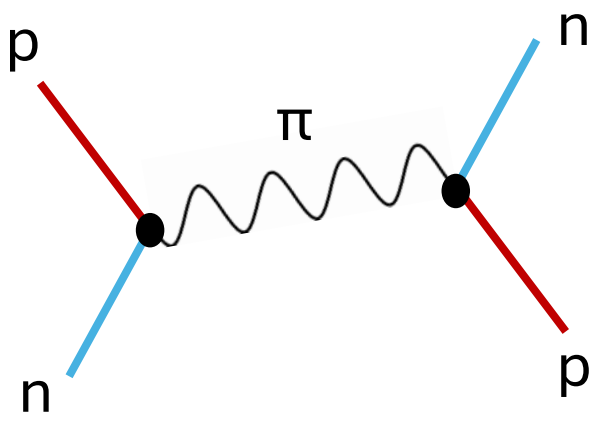
Nuclear theory for astrophysics:
Bridging bound-state and continuum physics
ECT*, Trento, 22 May 2026

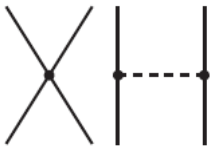
The ab initio approach

Nucleons as degrees of freedom

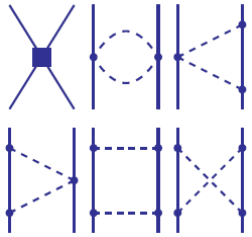


Interactions are described by two- and three-nucleon forces

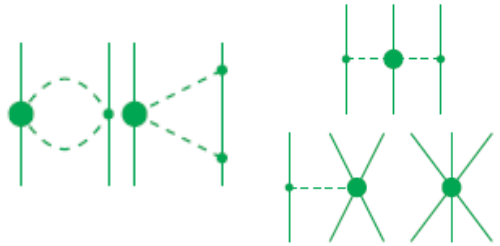
LO (Q^0)



NLO (Q^2)



NNLO (Q^3)



Chiral effective field theory

Machleidt et al., PPNP **137**, 104117 (2024)

Coupled-cluster (CC) theory

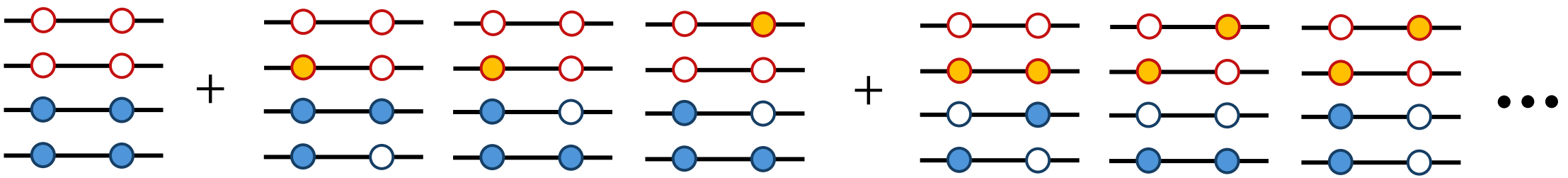
CC ground-state wave function $|\Psi_0\rangle = e^T |\Phi_0\rangle$

CCSDT-1: approximate triples

$T \approx T_1 + T_2 + T_3 + \cdots$

CCSD

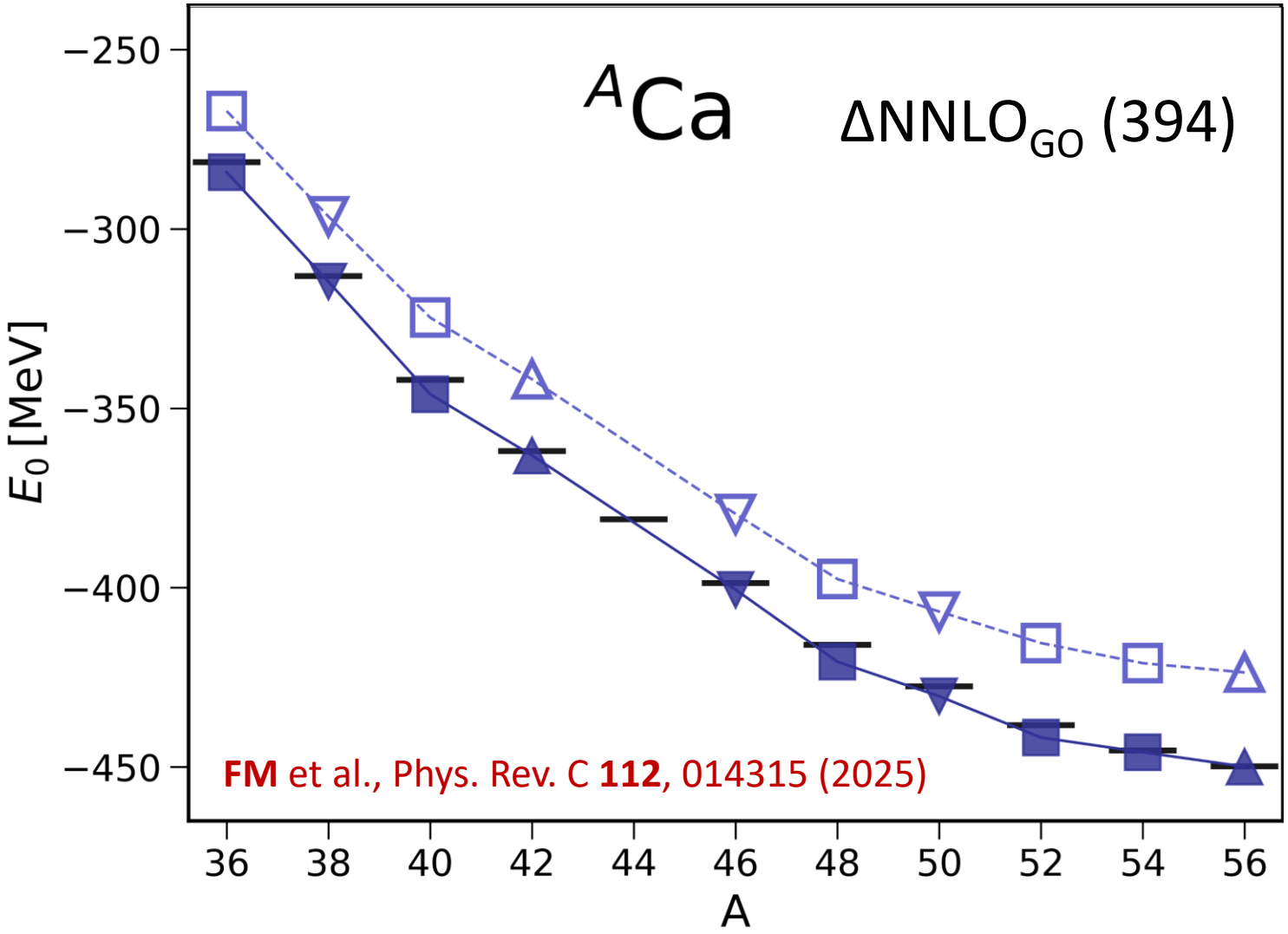
n-particle n-hole amplitudes

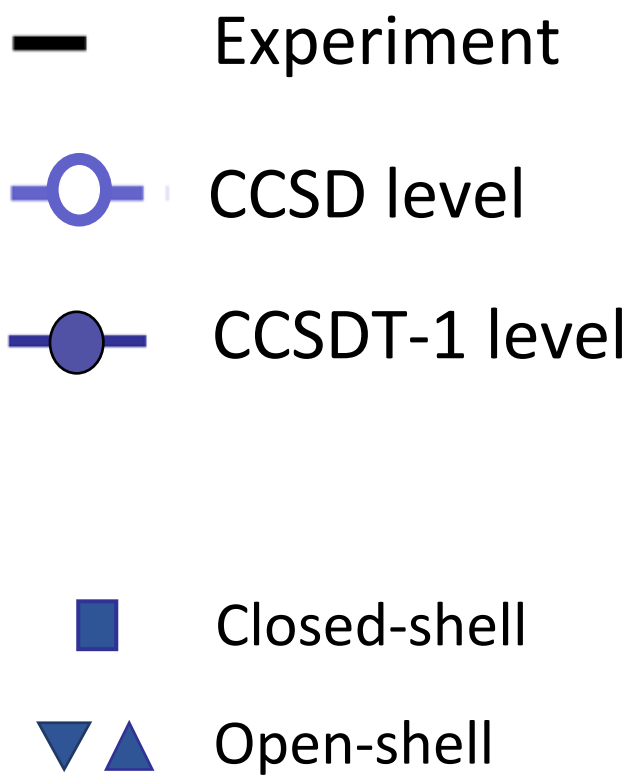
$|\Psi_0\rangle =$ 

$|\Phi_0\rangle$ $1p1h$ excitations $2p2h$ excitations

Hagen et al., Rep. Prog. Phys. **77**, 096302 (2014)

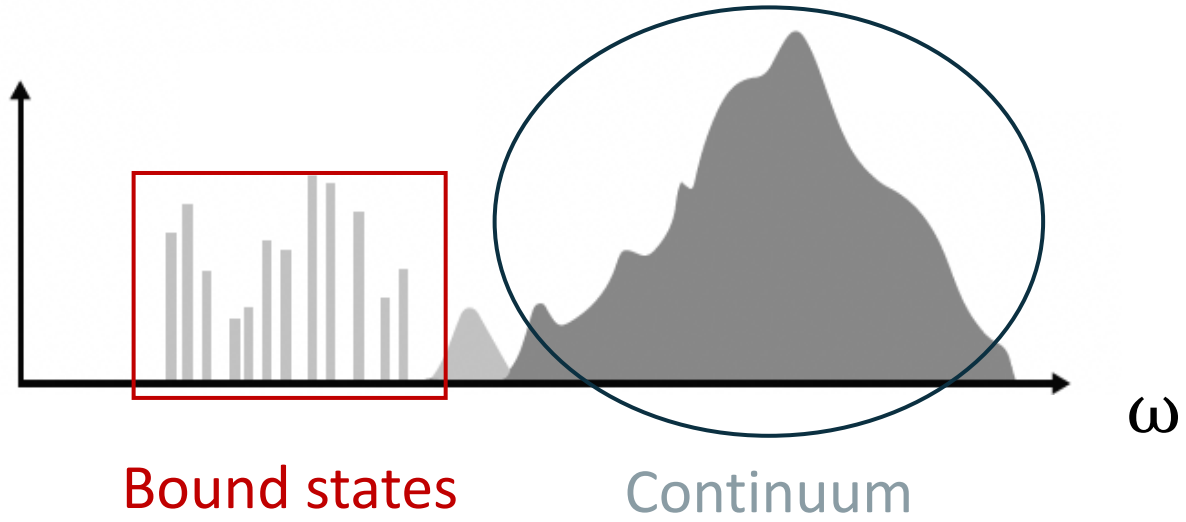
Impact of triples





Electromagnetic response functions: Towards neutron-rich isotopes

Beyond the ground state



Nuclear response function

$$R(\omega) = \sum_f \left|\langle \Psi_f | \Theta | \Psi_0 \rangle\right|^2 \delta(E_f - E_0 - \omega)$$

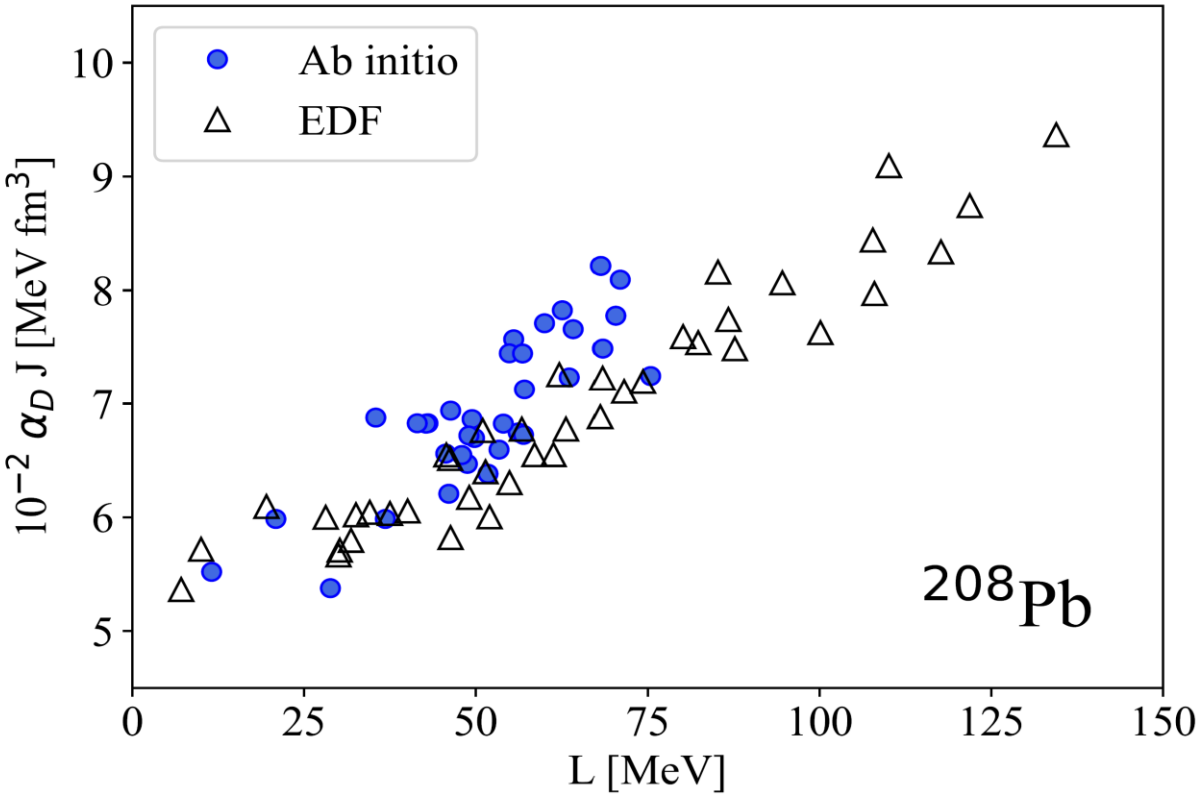
Θ: excitation operator

The electric dipole polarizability

Electric dipole polarizability $\alpha_D = 2\alpha \int d\omega \frac{R(\omega)}{\omega}$

$R(\omega)$: dipole response function

Courtesy: Francesca Bonaiti



Strong linear correlation between α_D and the slope of the nuclear matter symmetry energy *L*

Neumann-Cosel et al., Front. Phys. **13**, 1629987 (2025)

The Lorentz integral transform (LIT) method

Map R(ω) to its convolution with a Lorentzian kernel

$$L(\sigma,\Gamma) = \frac{\Gamma}{\pi}\int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2} = \frac{\Gamma}{\pi}\langle\widetilde{\Psi}_L(z^*)|\widetilde{\Psi}_R(z)\rangle$$

$$(\bar{H}-z)\left|\widetilde{\Psi}_R(z)\right\rangle = \bar{\Theta}|\Phi_0\rangle$$

$|\widetilde{\Psi}_R\rangle$ is a pseudo bound state

$$z = \sigma + i\Gamma$$

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

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

Sum rules of the response directly from $L(\sigma,\Gamma\to 0)$

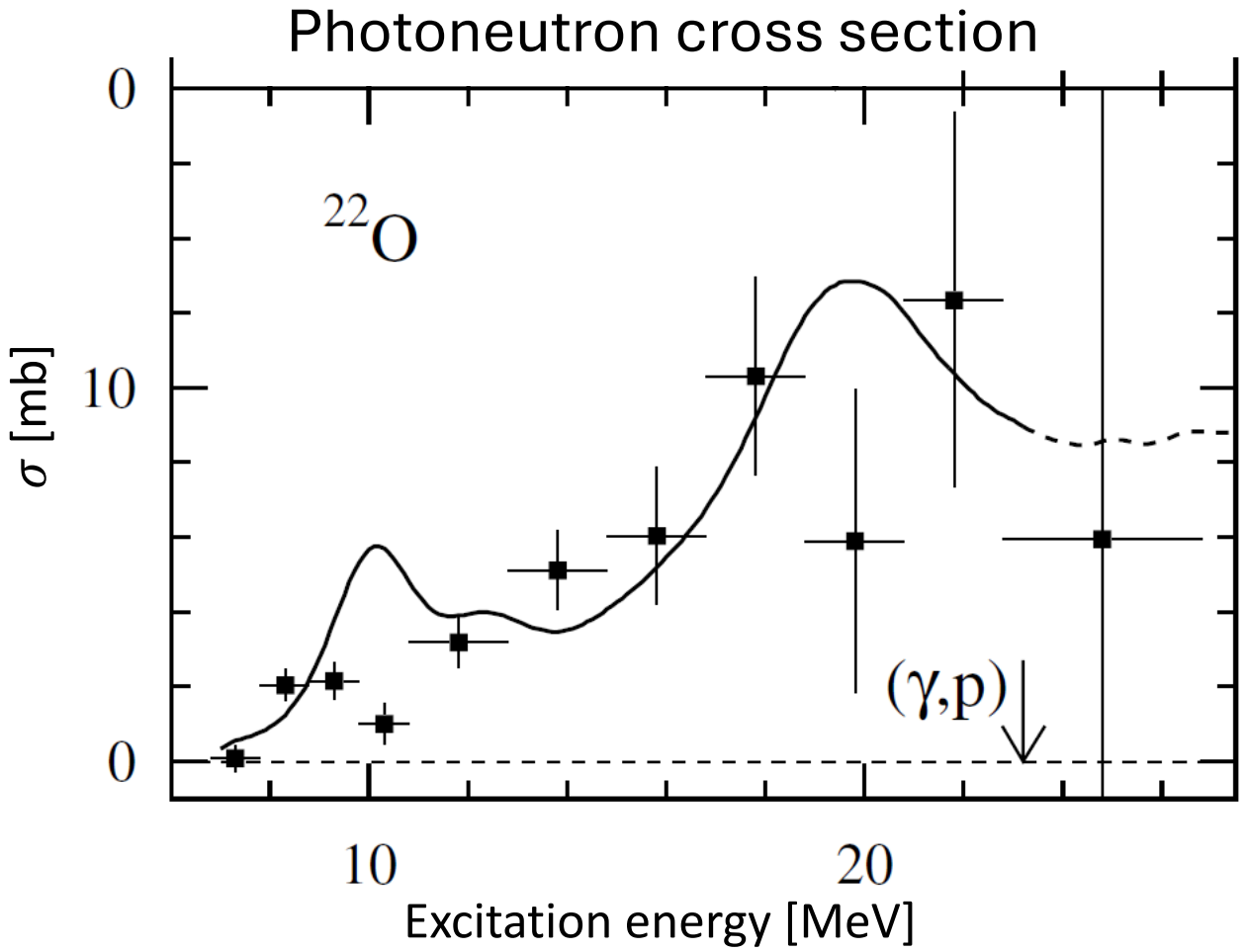
Need to reconstruct $R(\omega)$ from the LIT

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

S. Bacca, **FM**, and A. Porro, arXiv:2604.07229 [contribution to Encyclopedia of Nuclear Physics]

On the neutron-rich side: the case of ^{22}O

^{22}O is one of the few neutron-rich nuclei for which the dipole response has been measured

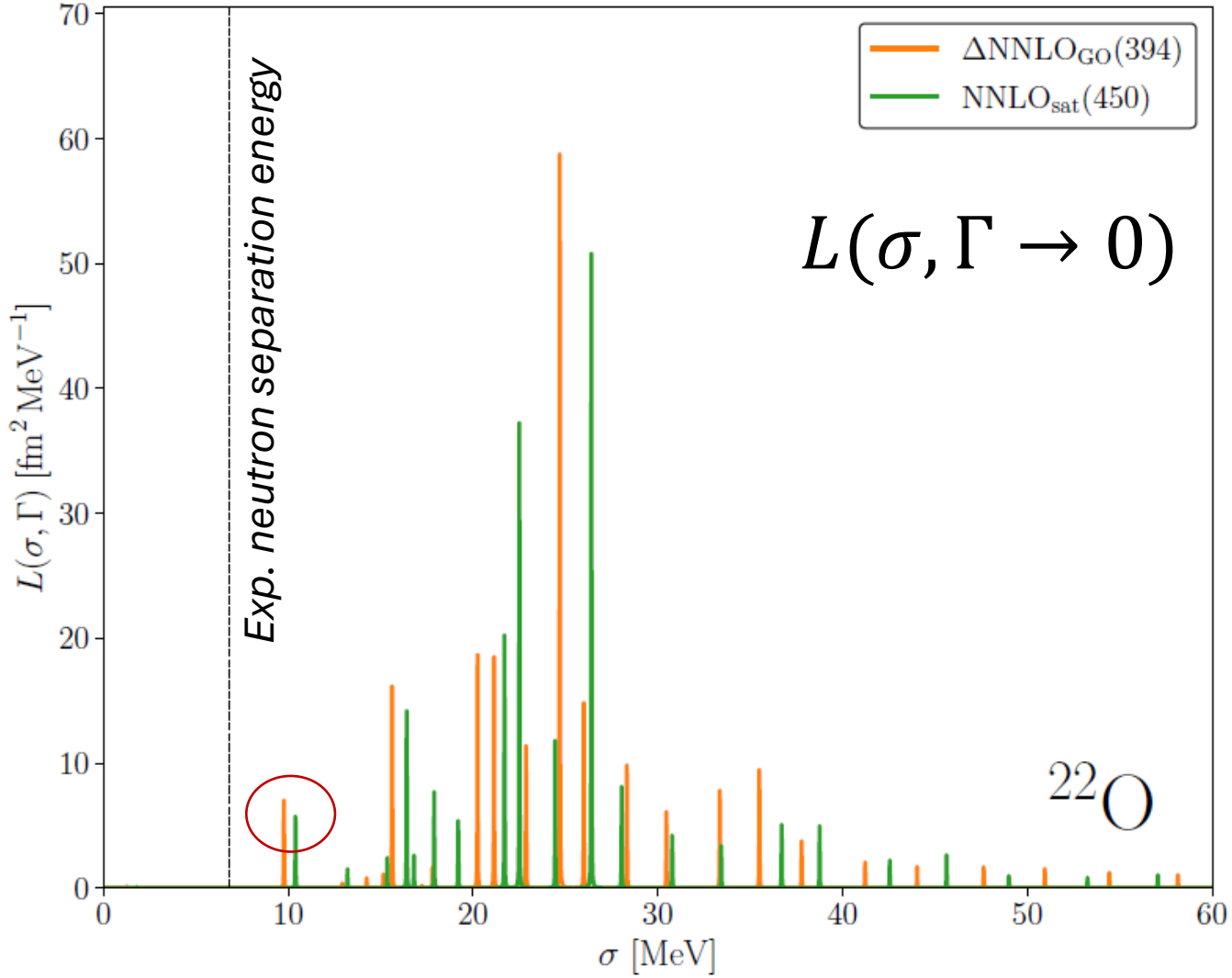


Photoneutron cross-section extracted from electromagnetic excitations cross-sections

Leistenschneider et al., Phys. Rev. Lett. 86, 5442 (2001)

Theory predictions: the LIT

Discretized response functions

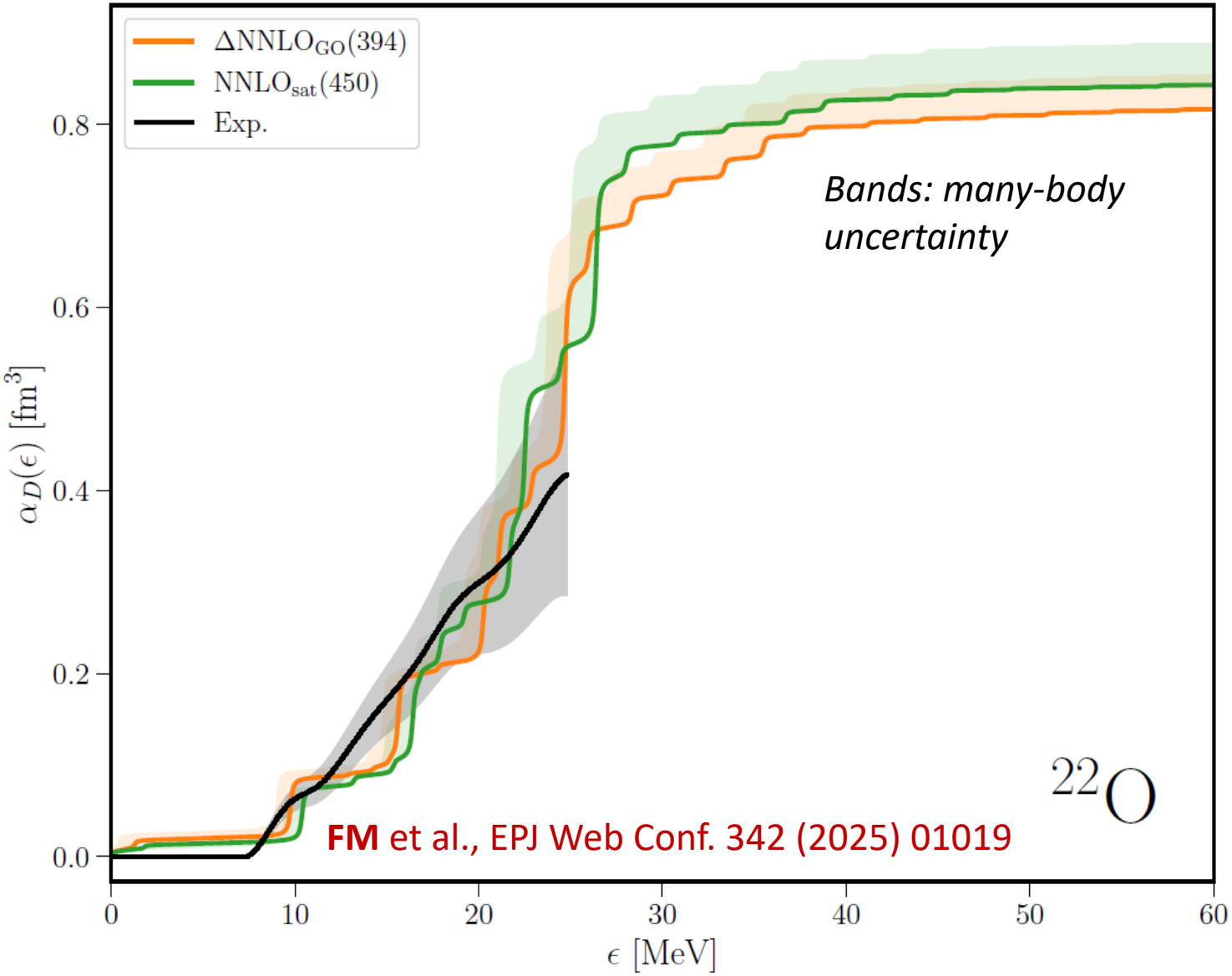


Calculations at the CCSDT-1 level

LIT-CC consistently predicts low-lying strength near the neutron threshold

The ^{22}O electric dipole polarizability

Polarizability running sum



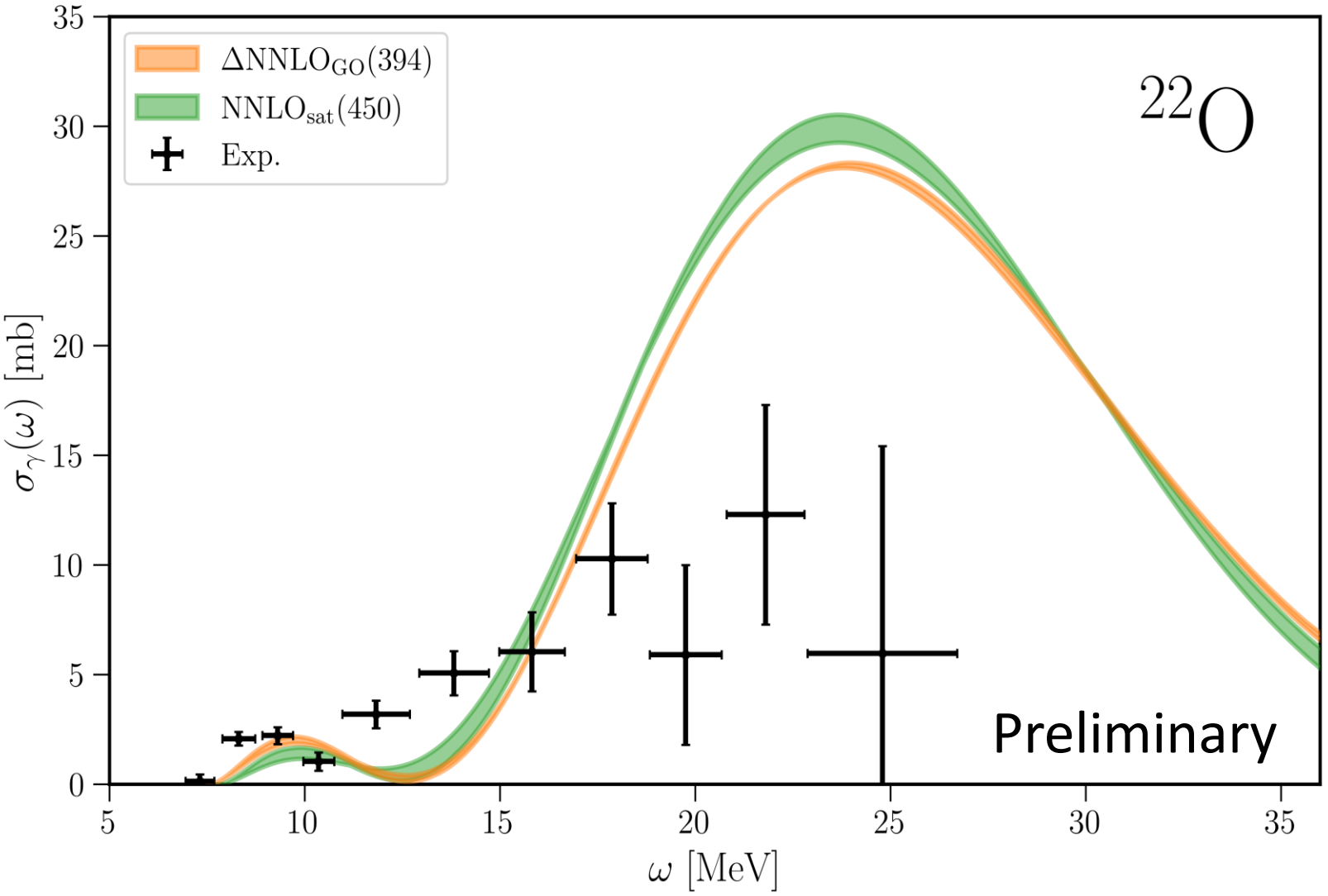
$$\alpha_D(\epsilon) = 2\alpha\hbar c \int_0^{\epsilon} d\sigma \frac{L(\sigma, \Gamma')}{\sigma}$$

$\Gamma' = 10^{-4}$ MeV

Good agreement between theory and experiment (up to 25 MeV)

^{22}O cross section

Courtesy: Miriam El Batchy

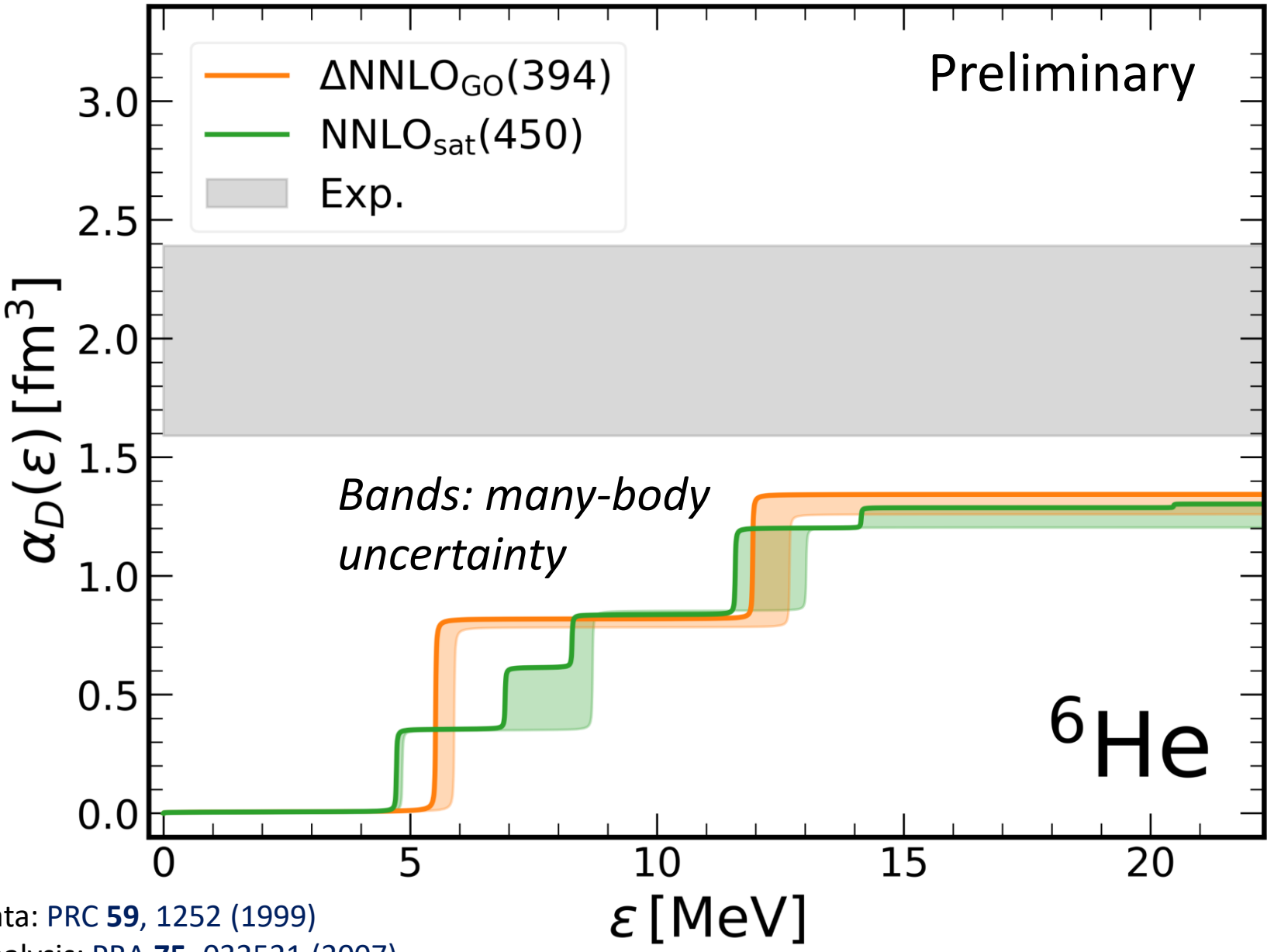


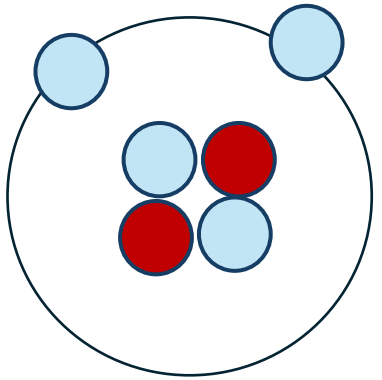
$$\sigma_\gamma(\omega) = 4\pi^2\alpha\omega R(\omega)$$

Exp. photoneutron cross sections from [Phys. Rev. Lett. 86, 5442 (2001)]

Cross sections with quantified **uncertainties** from the **inversion** of the LIT

Polarizability of the halo-nucleus ^{6}He





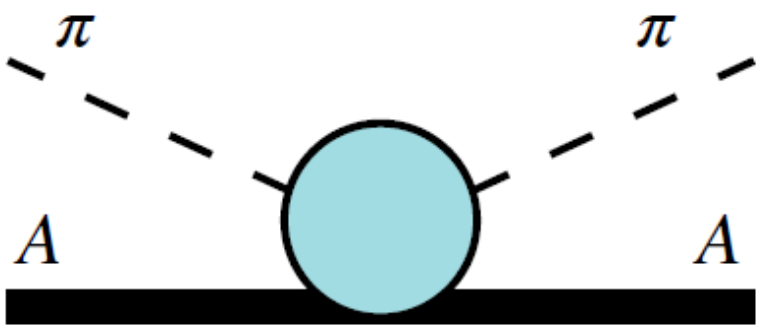
Two-particle-attached/removed formalism:
Bonaiti et al., PRC **110**, 044306 (2024)
FM et al., PRC **112**, 014315 (2025)

Data: PRC **59**, 1252 (1999)
Analysis: PRA **75**, 032521 (2007)

Bridging structure and reactions: Pion-nucleus elastic scattering

Motivation

Goal: understanding pion-nucleus elastic scattering using advanced nuclear **reaction** models combined with *ab initio* description of the **structure** of the target



V. Tsaran**, FM** et al., Phys. Rev. C **112**, 034608 (2025)

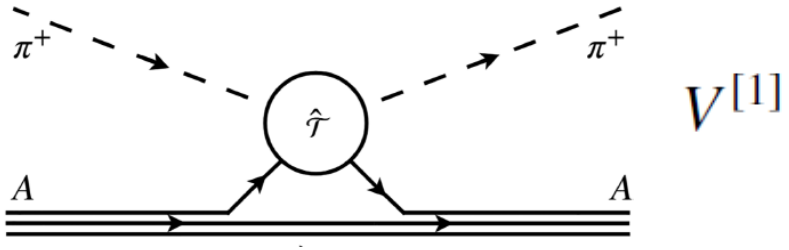
A primer on (multiple) scattering theory

$$F(\boldsymbol{k}', \boldsymbol{k}) = V(\boldsymbol{k}', \boldsymbol{k}) - \frac{A-1}{A} \int \frac{\mathrm{d}\boldsymbol{k}''}{2\pi^2} \frac{V(\boldsymbol{k}', \boldsymbol{k}'')F(\boldsymbol{k}'', \boldsymbol{k})}{k_0^2 - k''^2 + i\,\varepsilon}$$

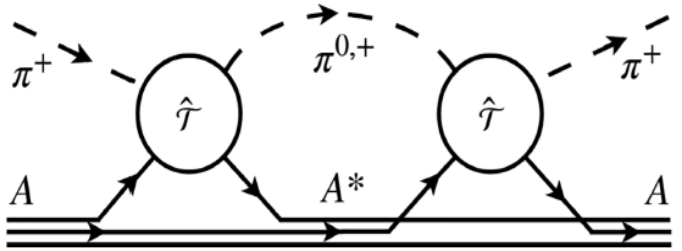
F: Elastic scattering amplitude

V: Pion-nucleus scattering potential

$$V(\boldsymbol{k}', \boldsymbol{k}) \approx V^{[1]}(\boldsymbol{k}', \boldsymbol{k}) + V^{[2]}(\boldsymbol{k}', \boldsymbol{k})$$



$V^{[1]}$

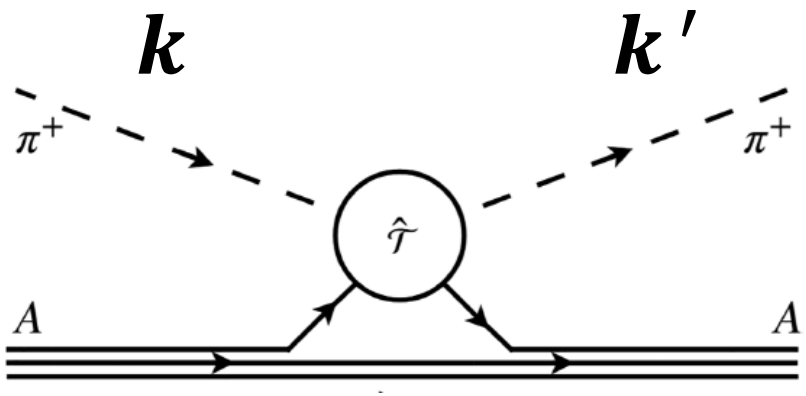


$V^{[2]}$

V. Tsaran et al., Phys. Rev. C **108**, 044608 (2023)

V. Tsaran**, FM** et al., Phys. Rev. C **112**, 034608 (2025)

Leading-order scattering potential



$$\boldsymbol{q} = \boldsymbol{k}' - \boldsymbol{k}$$

$$V^{[1]}(\boldsymbol{k}', \boldsymbol{k}) = \mathscr{W}(\boldsymbol{k}', \boldsymbol{k})\mathrm{Tr}[\hat{f}(\boldsymbol{k}', \boldsymbol{k})\rho(\boldsymbol{q})]$$

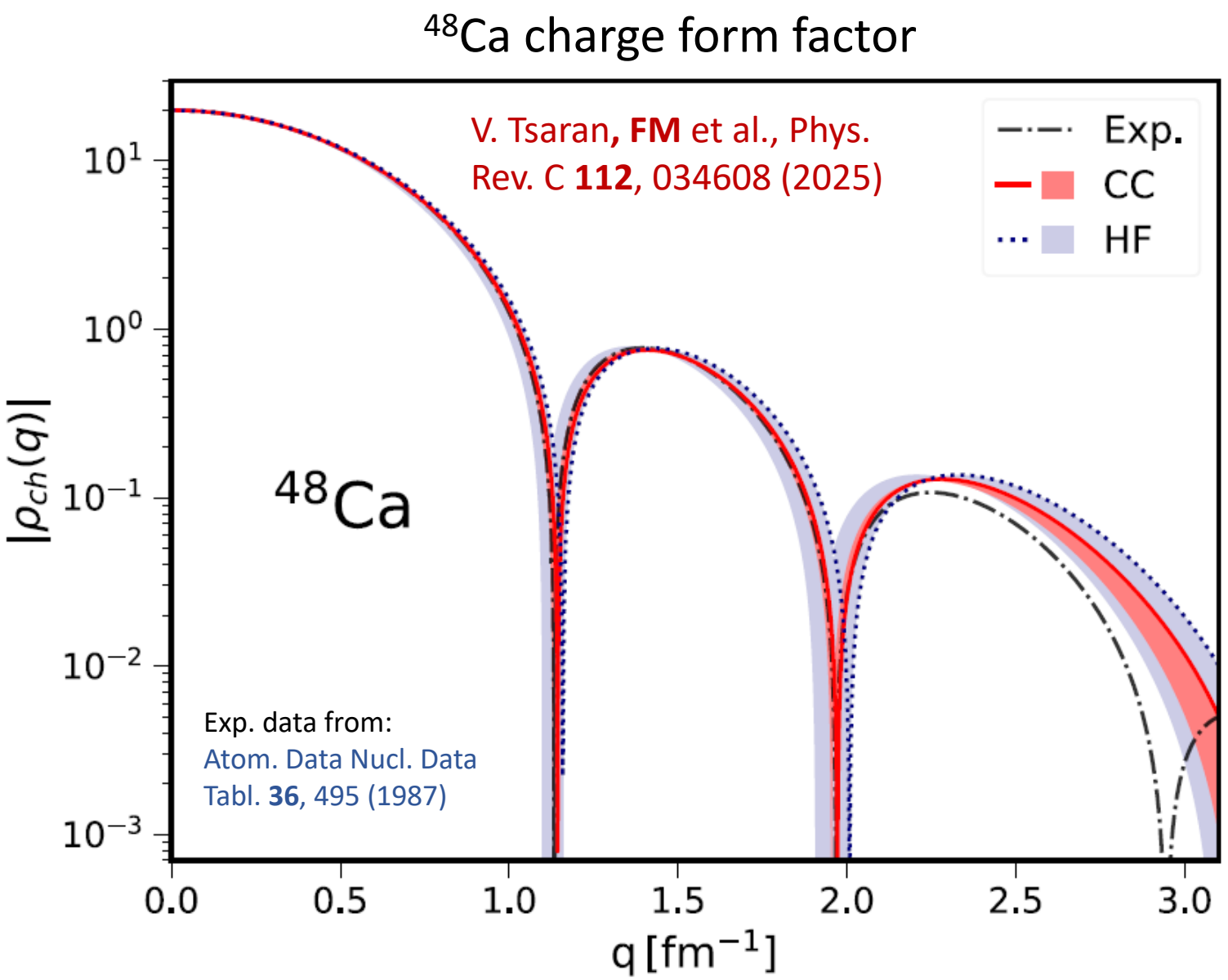
$\hat{f}$: Pion-nucleon amplitude

$\rho(\boldsymbol{q})$: One-nucleon form factors

⟹ Need proton and neutron form factors from theory!

Tsaran et al., Phys. Rev. C **108**, 044608 (2023)

Form factors



Coupled-cluster – CCSDT-1

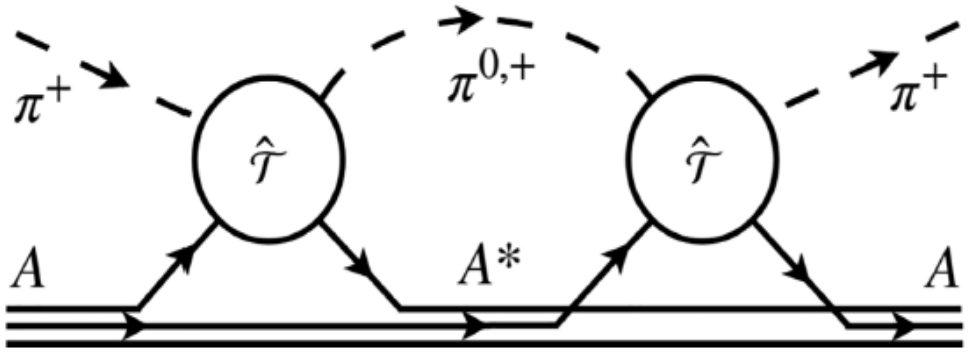
Hartree-Fock

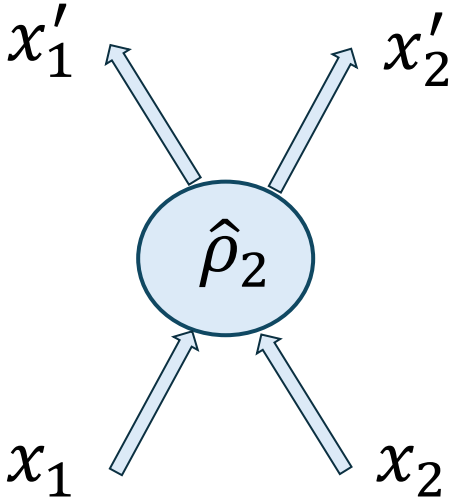
Mild interaction dependence (shaded band)

Excellent agreement up to the second minimum

Second-order scattering potential

$V^{[2]}$



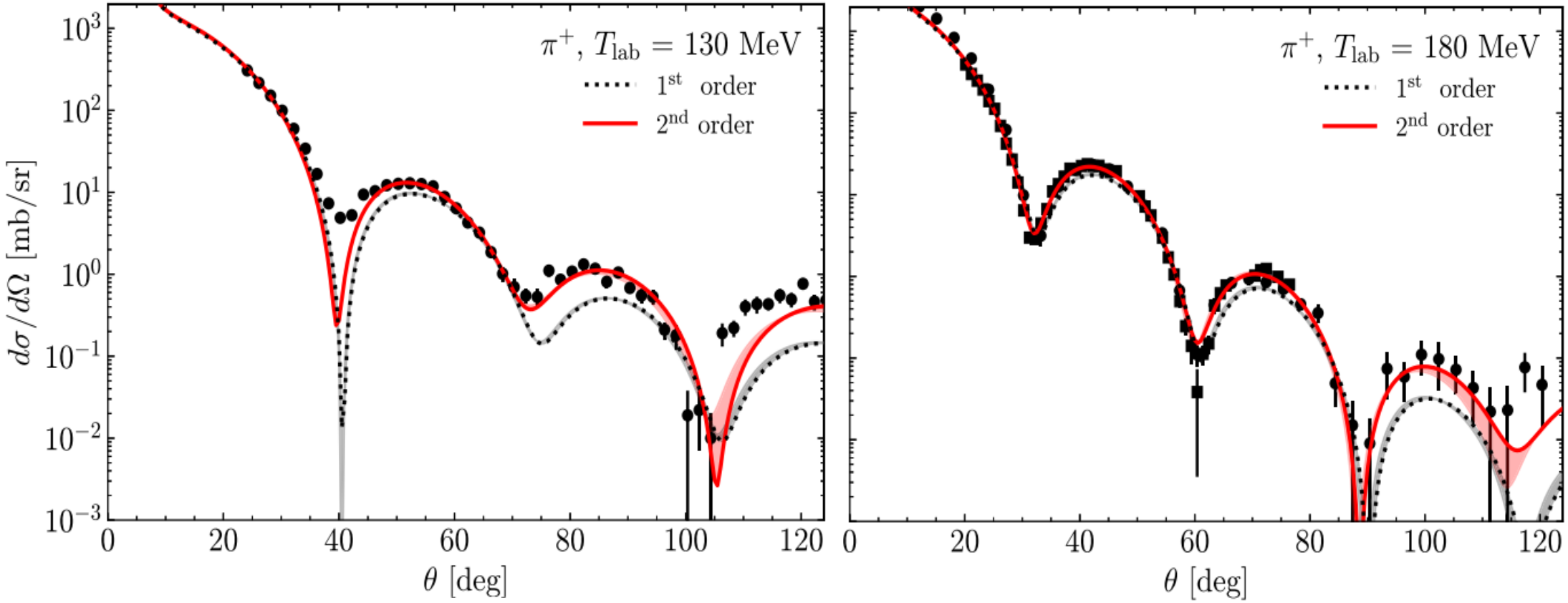


Two-body density matrix

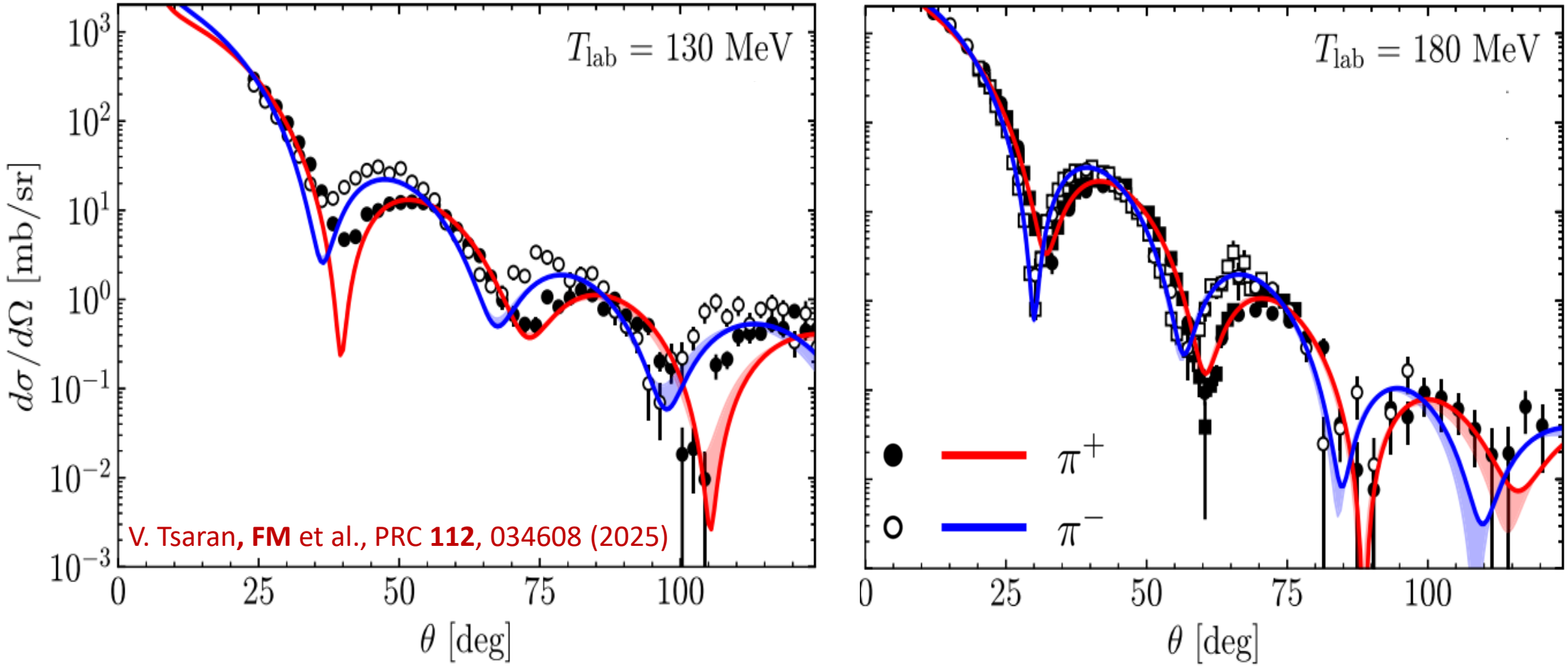
$$\hat{\rho}_2(x_1'x_2'; x_1x_2) = \hat{\psi}^+(x_1')\,\hat{\psi}^+(x_2')\hat{\psi}(x_2)\hat{\psi}(x_1)$$

Impact of the second-order potential

π^+-^{48}Ca elastic cross sections

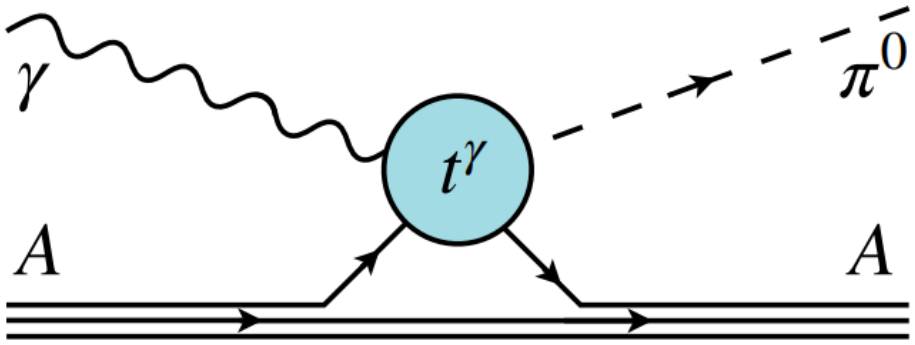


Pion-nucleus cross sections



Good description of the experimental cross-sections with controlled nuclear-structure uncertainties

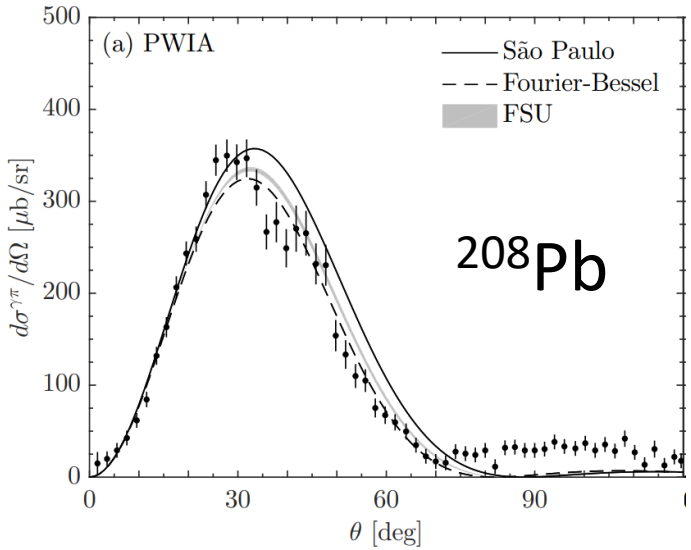
Neutron skins from coherent pion photoproduction?



Neutral pions are sensitive to the total density.

Is pion photoproduction sensitive to the neutron skin?

Colomer et al., PRC **106**, 044318 (2022)



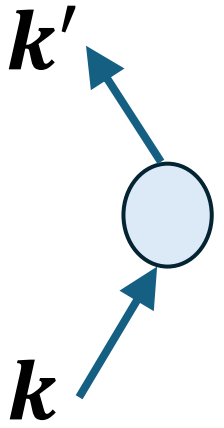
Tarbert et al., Phys. Rev. Lett. **112**, 242502 (2014)
Tsaran et al., Phys. Rev. C **110**, 014605 (2024)

Electroweak cross sections from nuclear matter spectral functions

Motivation

Electroweak cross sections

$$\frac{d^2\sigma}{dE'_k d\Omega'_k} = \kappa \frac{|\boldsymbol{k}'|}{|\boldsymbol{k}|} \frac{1}{4E_p E_{p'}} L_{\mu\nu}(k,k') W^{\mu\nu}(q)$$



L: leptonic tensor
W: hadronic tensor

Work by Alma Cavallin, FM, and Joanna Sobczyk

Local density approximation for EW processes

Impulse approximation: the interaction takes place with a single nucleon

$$W^{\mu\nu}(q) = \int d^3r \int \frac{d^3p}{(2\pi)^3} \int dE S^h[E, \boldsymbol{p}; \rho(r)] S^p[E + \omega, \boldsymbol{p} + \boldsymbol{q}; \rho(r)] \frac{m_N}{E_p} \frac{m_N}{E_{p+q}} A^{\mu\nu}(p, q)$$

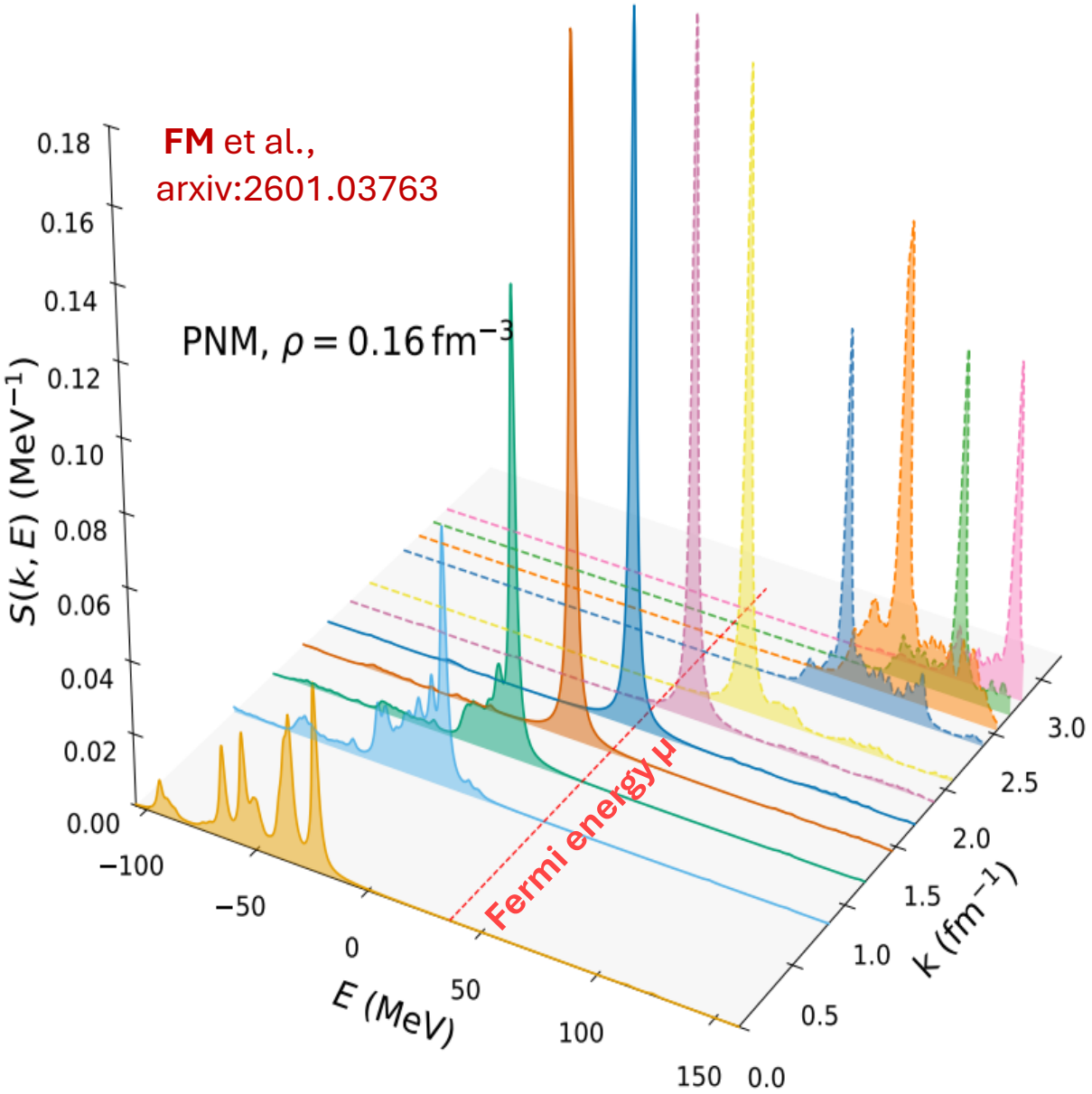
$S^{h/p}$: Hole/particle spectral functions

$A^{\mu\nu}$: Single-nucleon vertex

Local density approximation:
$S^{h/p}$ from nuclear matter + density profile ρ(r) from exp.

See e.g. Nieves, PRC 70, 055503 (2004); Rocco, Front. Phys. 8, 116 (2020); Sobczyk, PRC 109, 044314 (2024).

Introducing spectral functions



$S(k,E)$: probability of a nucleon having momentum *k* and energy *E* ("energy-resolved" density)

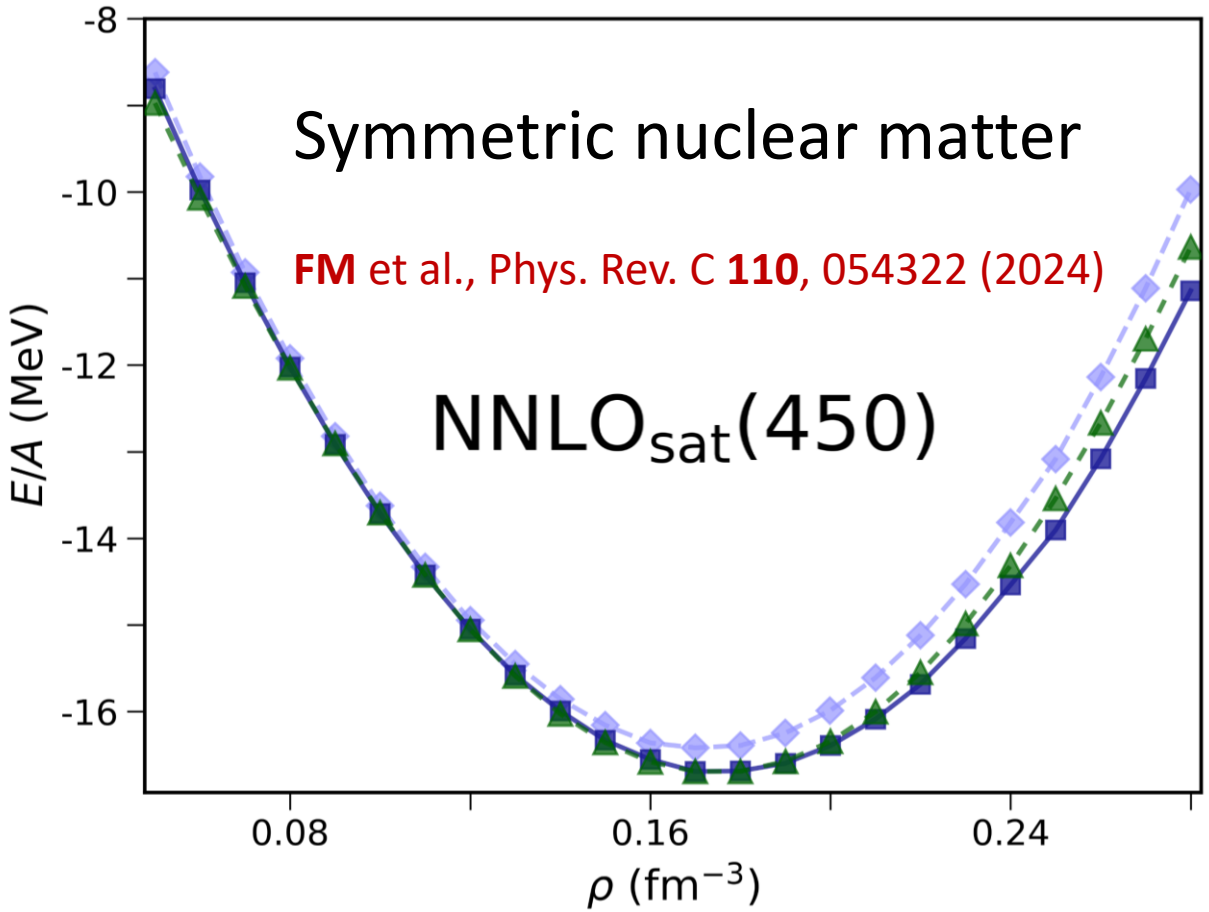
Hole part ($\epsilon_h < \mu$) Particle part ($\epsilon_p > \mu$)

$$S(k,E) = \sum_h A_h \delta(E - \epsilon_h) + \sum_p A_p \delta\left(E - \epsilon_p\right)$$

Algebraic diagrammatic construction

We determine the spectral functions using Green's function theory based on the Gorkov algebraic diagrammatic construction (ADC).

FM, C. Barbieri, and G. Colò, arxiv:2601.03763 [PRC in production]



ADC(3)

ADC(3)-D

Coupled-cluster - CCD(T)

ADC spectral functions

ADC provides a discrete-peak representation of $S(k,E)$

$$S(k,E) = \sum_h A_h \delta(E - \epsilon_h) + \sum_p A_p \delta\left(E - \epsilon_p\right)$$

Smooth out with a width Γ

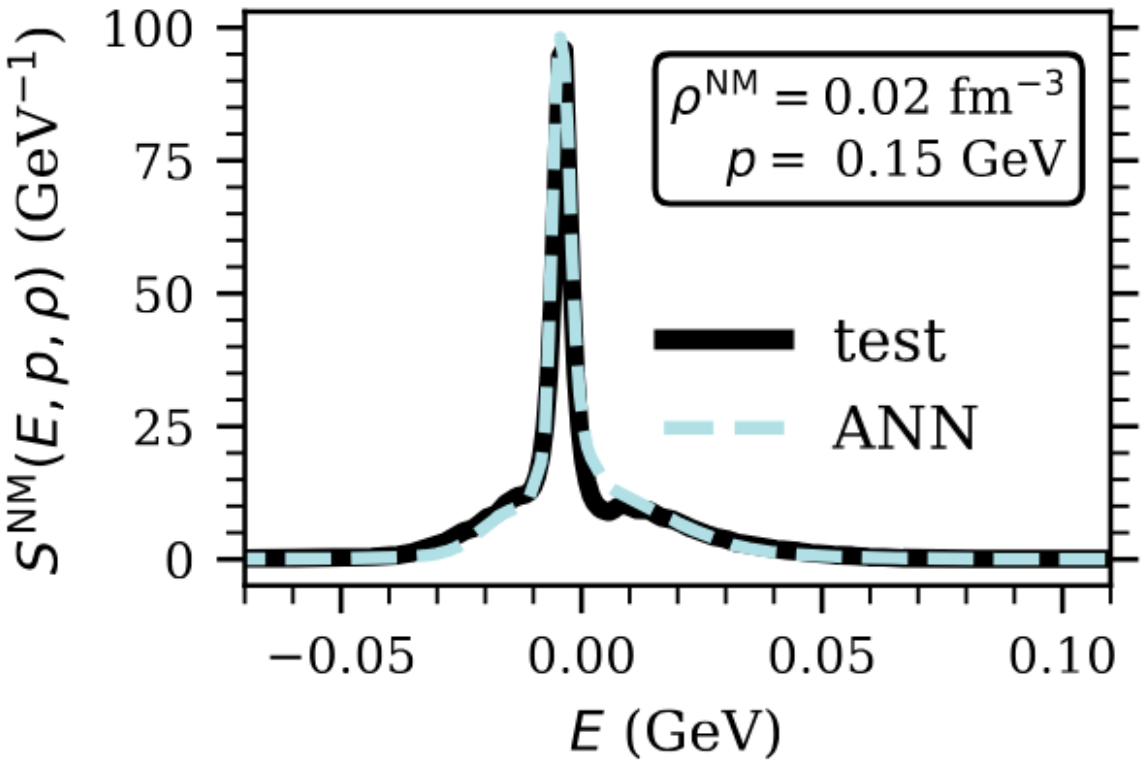
$$S_\Gamma(k,E) = \frac{\Gamma}{\pi} \sum_j \frac{A_j}{\left(E - \epsilon_j\right)^2 + \Gamma^2}$$

Cfr with the LIT concept Efros et al., J. Phys. G **34**, R459 (2007)

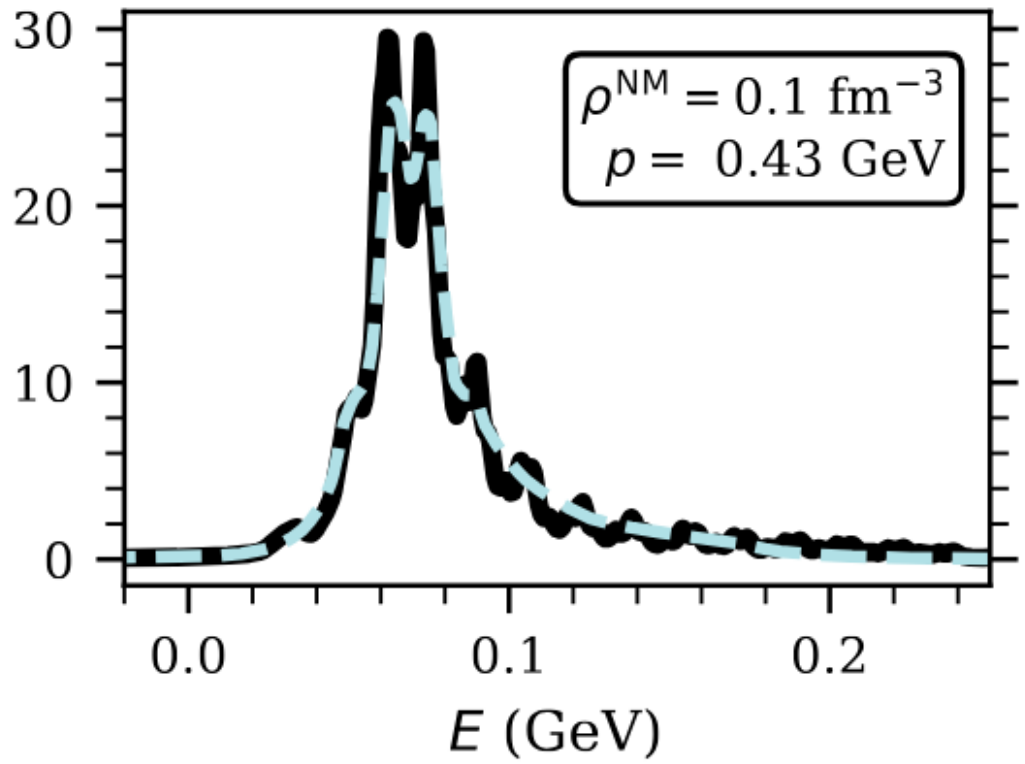
Learning the spectral function

Interpolate the spectral function using an artificial neural network (ANN)

Credit: Alma Cavallin

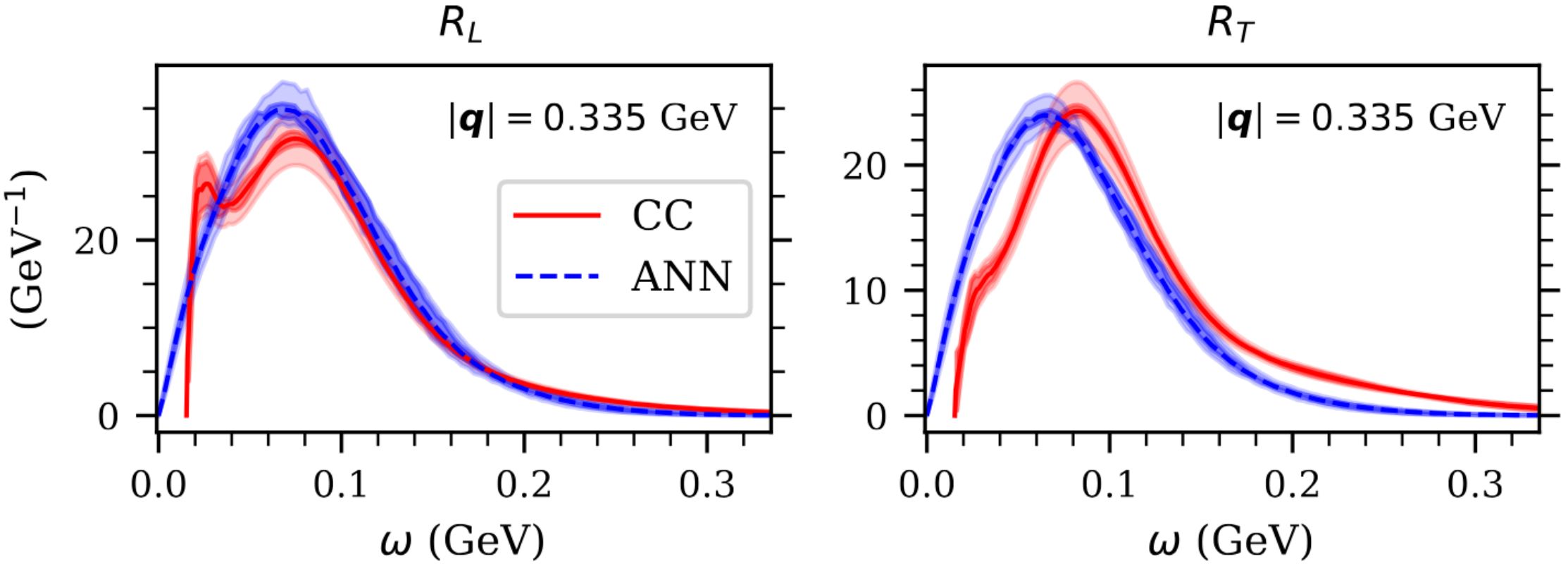


Symmetric nuclear matter. $NNLO_{sat}$ interaction.



Learn $S = S(\rho, k, \omega, \Gamma)$ for each interaction

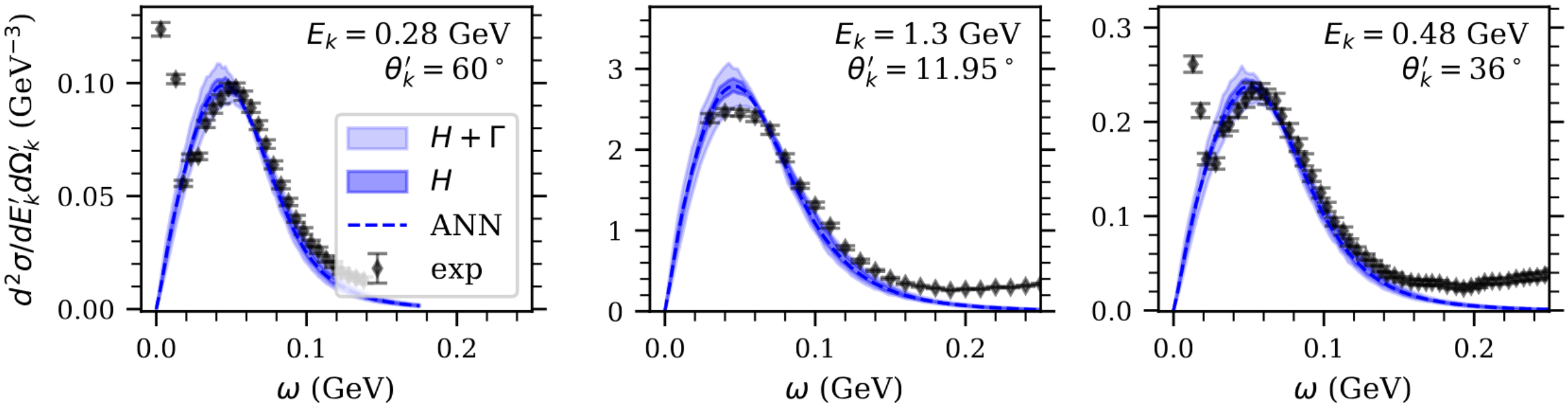
^{16}O electromagnetic response functions



"CC": LIT-CC calculations from Acharya et al., Phys.Rev.Lett. **134**, 202501 (2025)

^{12}C electromagnetic cross sections

Credit: Alma Cavallin



H Hamiltonian-dependence based on ΔNNLO$_{go}$(450), ΔNNLO$_{go}$(394), NNLO$_{sat}$

$H + \Gamma$ Dependence on both Hamiltonian and Γ (between 1 and 2 MeV)

Conclusions

- We have discussed applications of the LIT-CC method to compute the electric dipole polarizability in neutron-rich isotopes

- Multiple-scattering theory at second-order combined with realistic nuclear structure input yields accurate predictions of elastic pion-nucleus scattering

- We have studied electroweak cross sections based on nuclear matter spectral functions

Thank you for your attention!

Collaborators

- Mainz: Sonia Bacca, Miriam El Batchy, Weiguang Jiang, Viacheslav Tsaran, Marc Vanderhaeghen
- CEA: Andrea Porro
- Chalmers: Alma Cavallin, Joanna Sobczyk
- Darmstadt: Alex Tichai
- Knoxville: Thomas Papenbrock
- Milano: Carlo Barbieri, Gianluca Colò
- Oak Ridge: Francesca Bonaiti, Gaute Hagen, Gustav Jansen

Discussion

- Can we describe near-threshold phenomena (eg, pygmy resonances) ab initio?

  Brown et al., J. Phys. G: Nucl. Part. Phys. 52 050501 (2025)

- Can we exploit multiple-scattering theory at second-order for nuclear reactions (eg, elastic proton scattering)?

  Vorabbi et al., Phys. Rev. C **109**, 034613 (2024)

- What is the impact of two-body electroweak currents on the cross sections?

  Acharya et al., Phys.Rev.Lett. **134**, 202501 (2025)