Towards neutrino-nucleus scattering with coupled-cluster theory

Sonia Bacca

JG|U mitp

In collaboration with:

B. Acharya, L. Doria, G. Hagen, **W. Jiang,** M. Mihovilovich, T. Papenbrock, **C. Payne,**
I. Reis, J.E. Sobczyk

Neutrinos and nuclei

Are elusive

Symmetry magazine

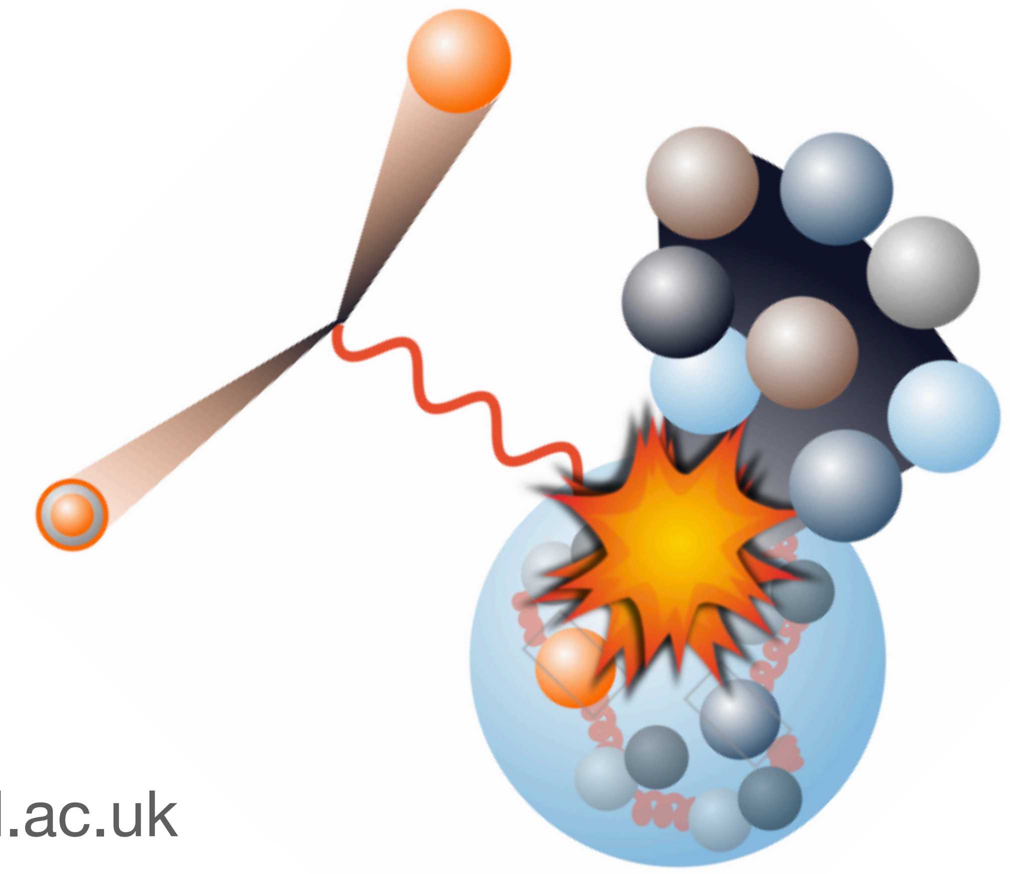
oscillate

Symmetry magazine

might be own antiparticles

APS Carin Cain

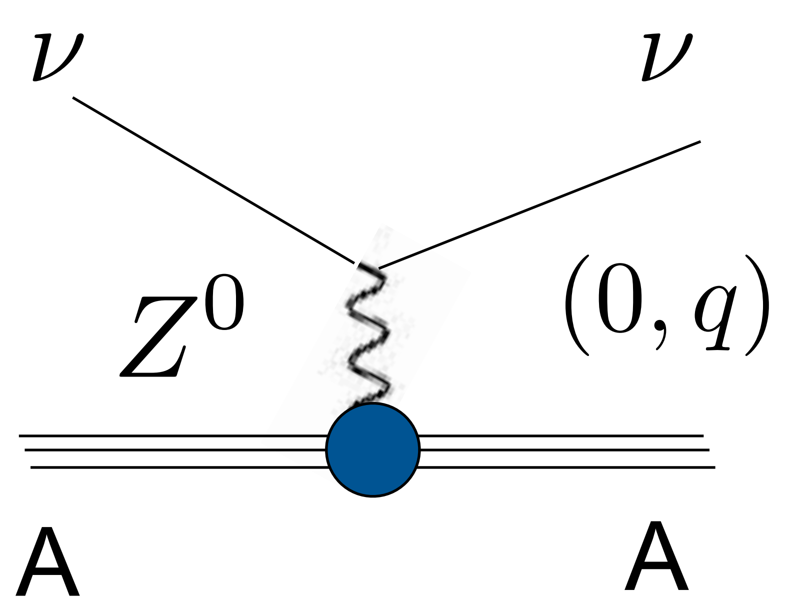
Their interactions with nuclei



ph.ed.ac.uk

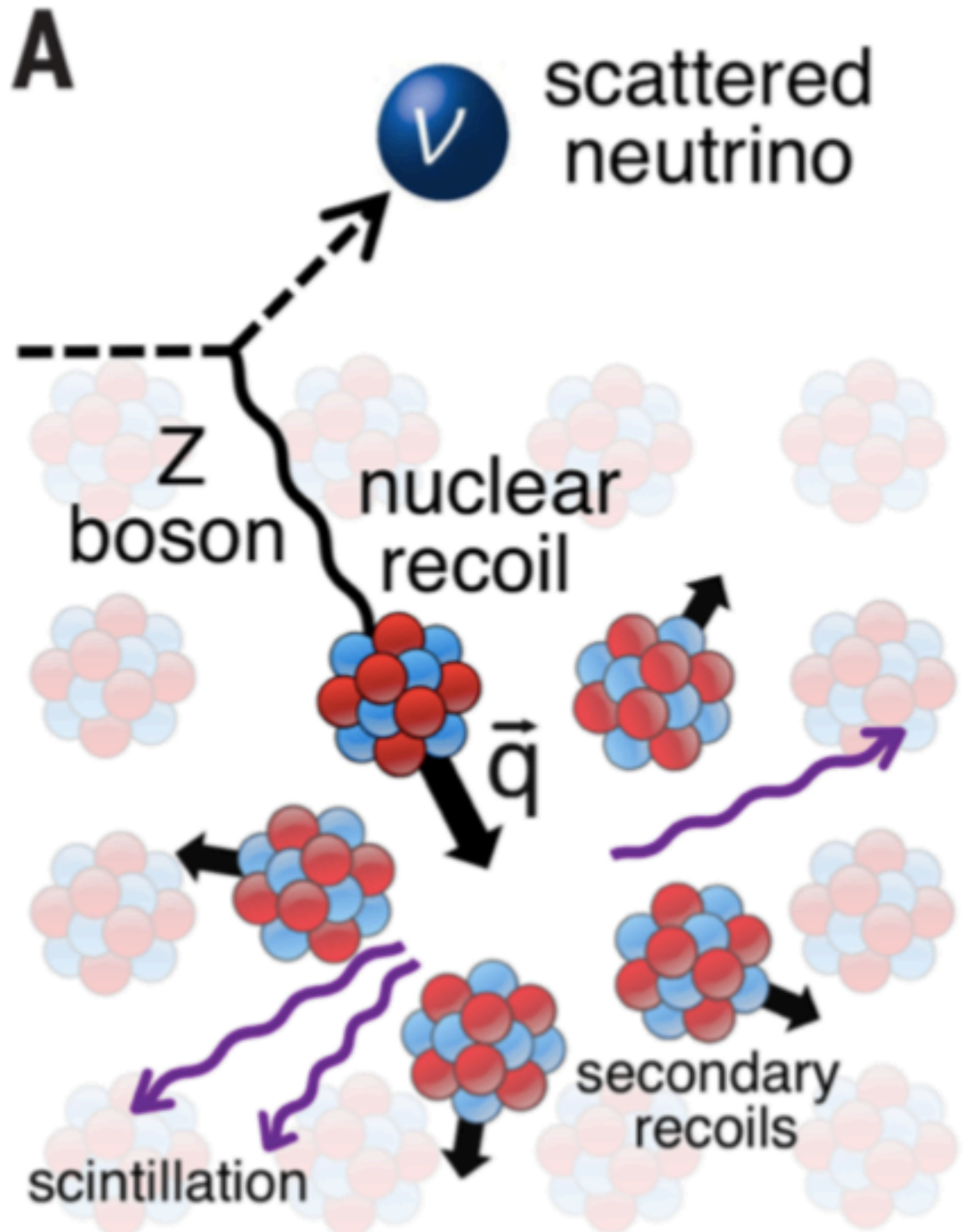
is essential for interpreting the results of neutrino experiments and understand their properties

Coherent elastic neutrino scattering (CEvNS)



The neutrino exchanges a Z-boson
with the nucleus, that recoils as a whole
(no internal excitation).

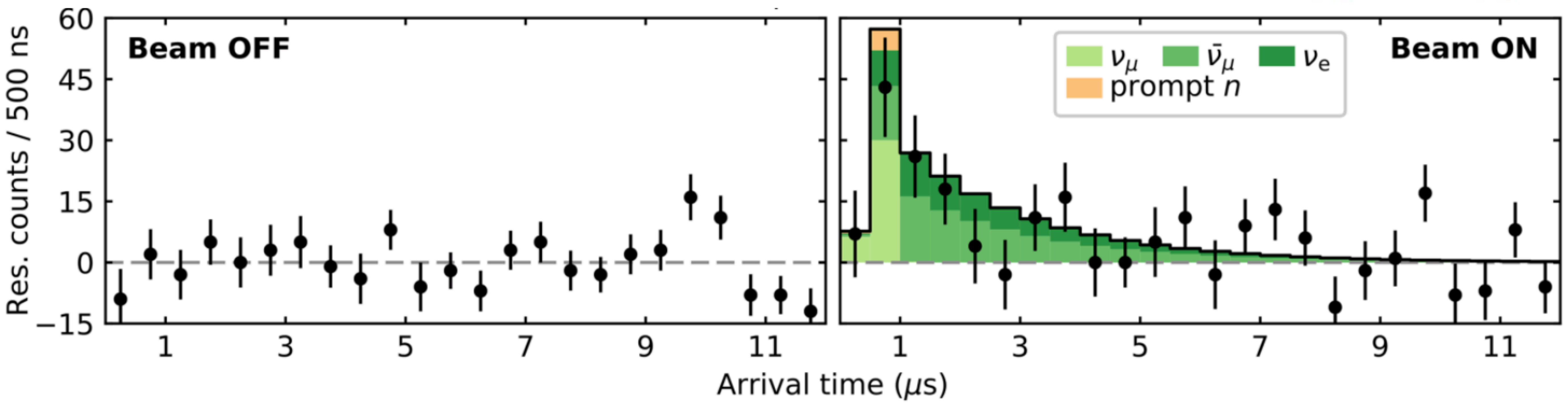
Coherent up to neutrino energies of 50 MeV



Signature: tiny energy deposited by nuclear recoils in the target material.

First proposed in Freedman, PRD (1974)

First observed in Akimov et al. Science (2017)

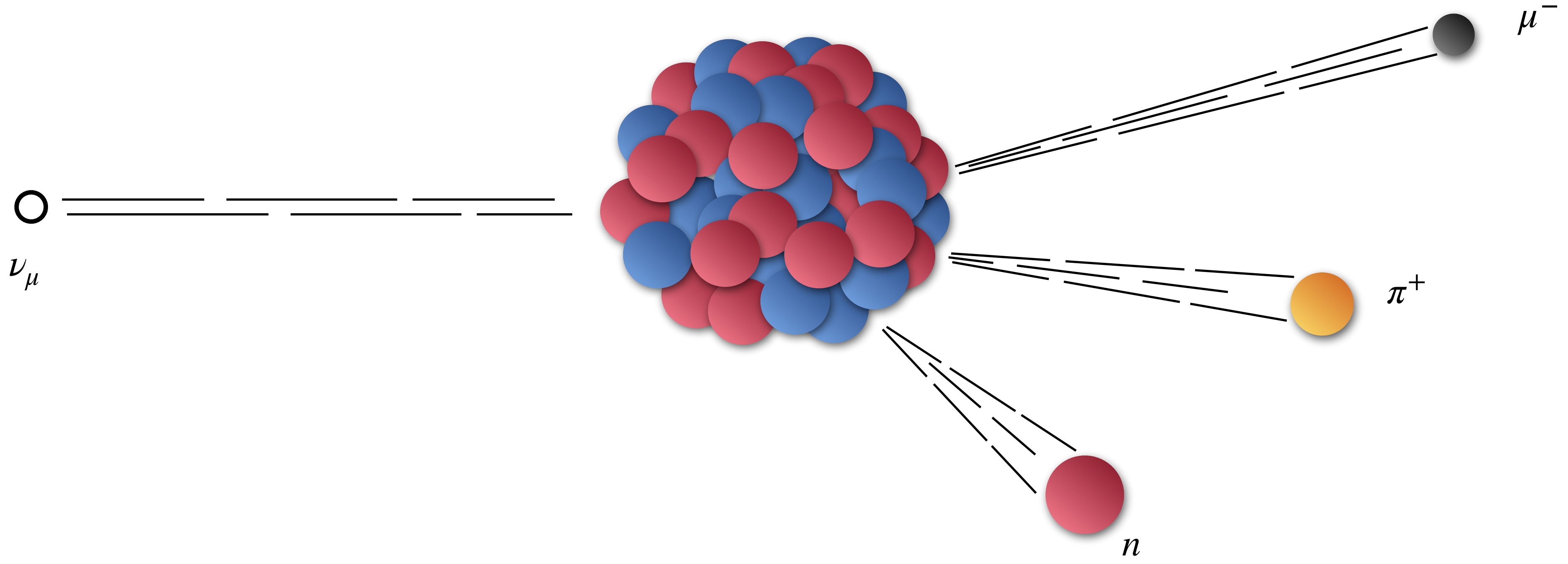


Target nuclei: Cs, I, Ar, Na, Ge

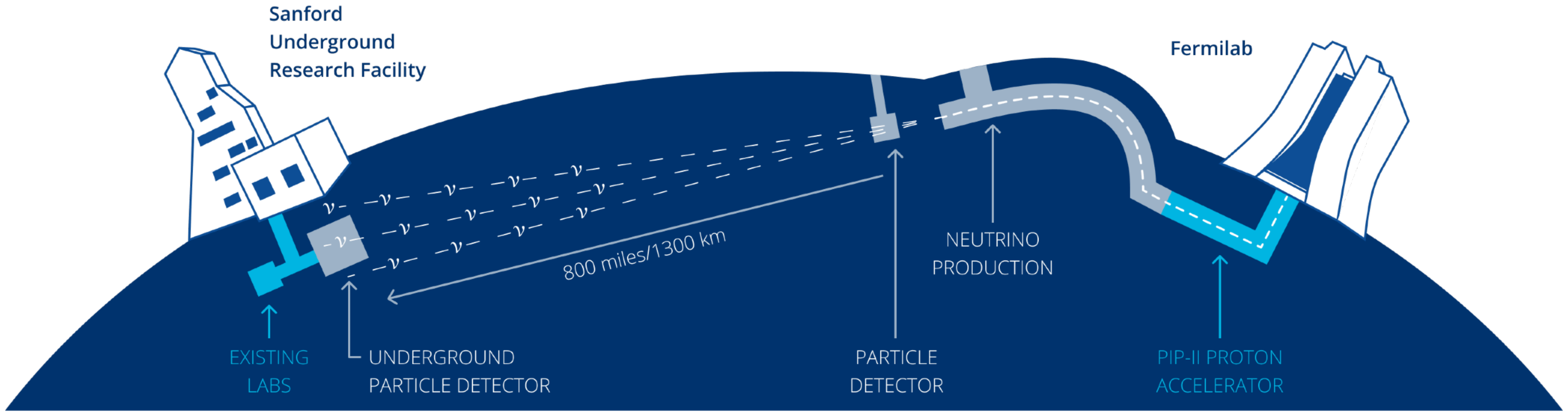
Neutrino oscillations

Next generation experiments

https://cerncourier.com/



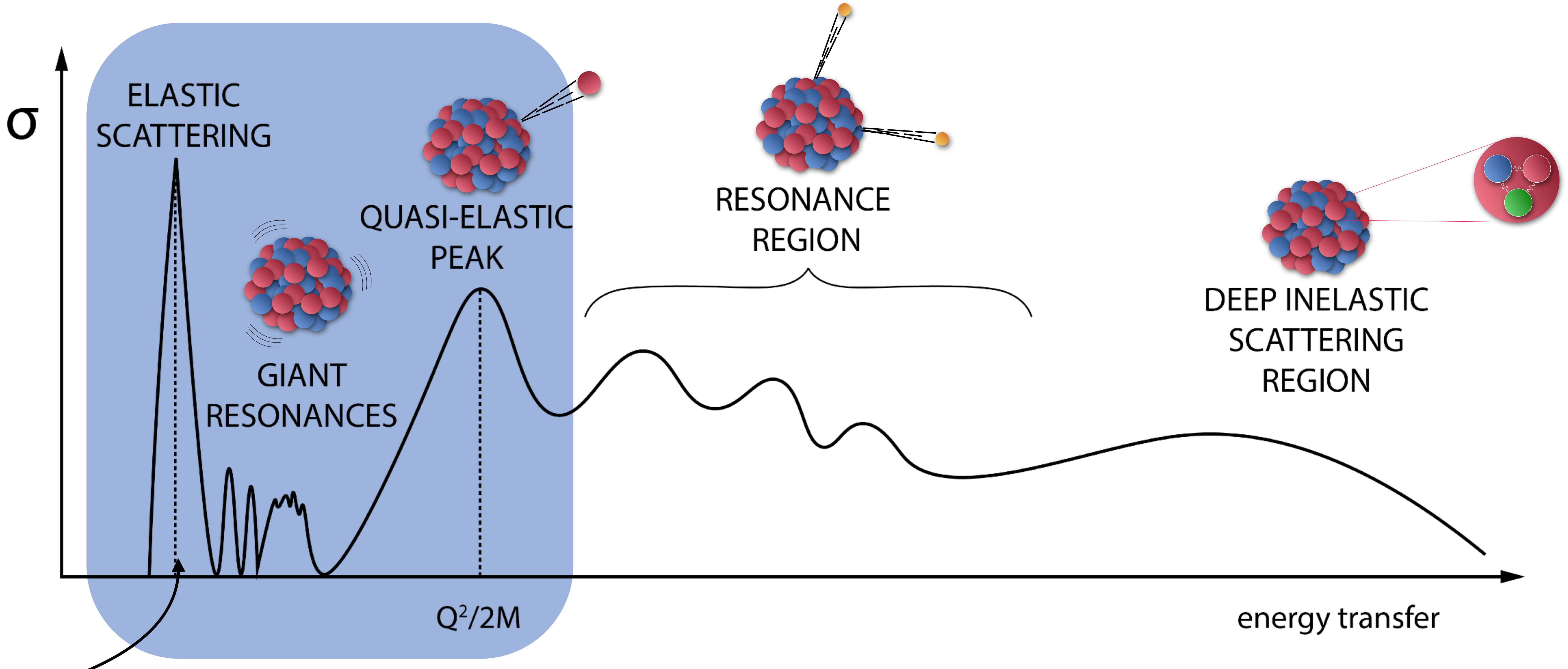
DEEP UNDERGROUND NEUTRINO EXPERIMENT



https://lbnf-dune.fnal.gov/

Target nuclei: ^{12}C, ^{16}O, ^{40}Ar

Neutrino-nucleus interactions



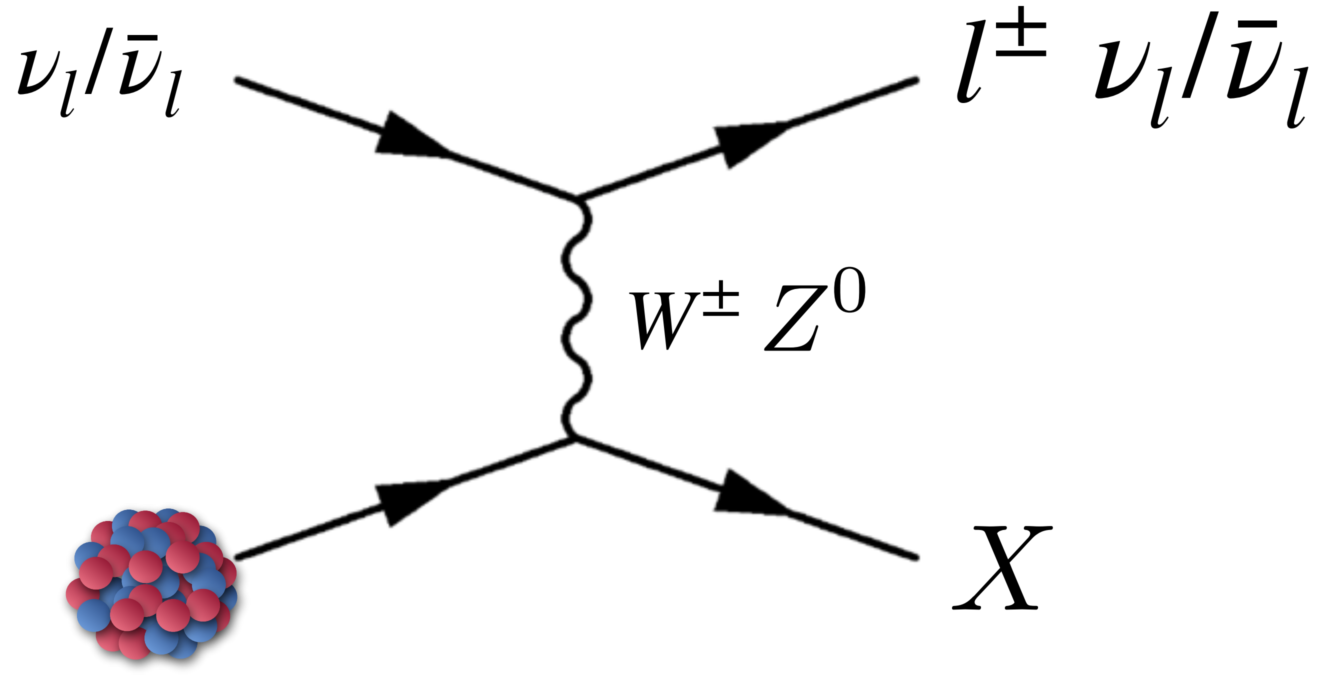
COHERENT SNS

Supernovae neutrinos

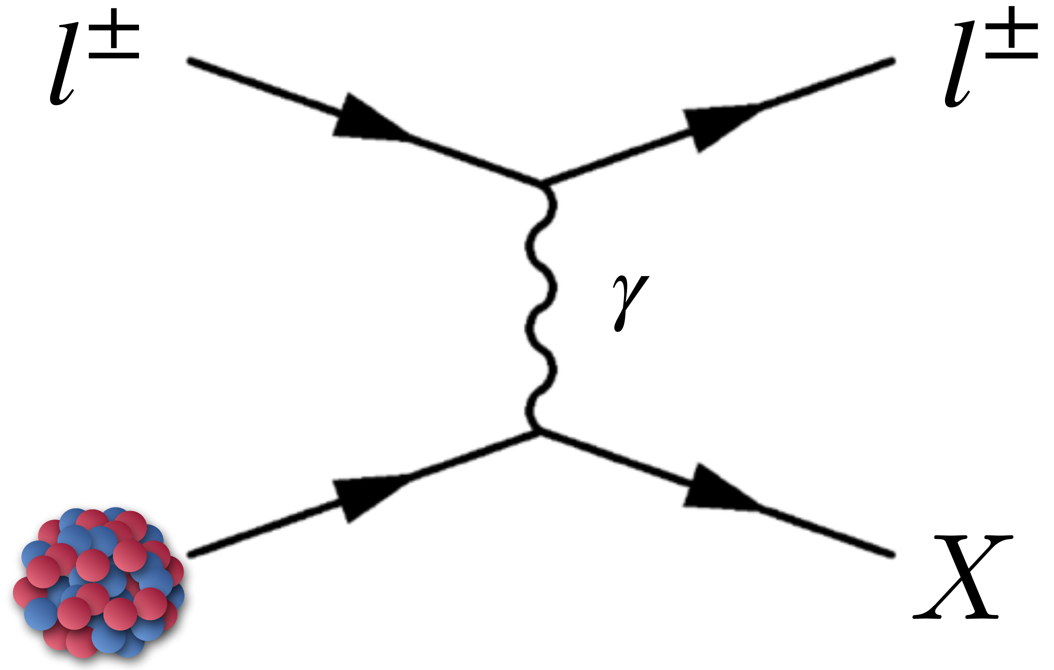
Long-baseline oscillation experiments (DUNE, HyperK)

Lepton-nucleus scattering

ν-A scattering



e-A scattering



Lepton-nucleus scattering

ν-A scattering

$$\left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\,\mathrm{d}\omega}\right|_{\nu/\bar{\nu}} = \sigma_0\left[\ell_{CC}R_{CC} + \ell_{CL}R_{CL} + \ell_{LL}R_{LL} + \ell_T R_T \pm \ell_{T'}R_{T'}\right]$$

e-A scattering

$$\left.\frac{d^2\sigma}{d\Omega d\omega}\right|_e = \sigma_M\left[\frac{Q^4}{q^4}R_L + \left(\frac{Q^2}{2q^2} + \tan^2\frac{\theta_e}{2}\right)R_T\right]$$

→ e4ν

E4ν goals

- Develop a solid theory that works for both electrons and neutrinos
- Use electron-scattering data to validate the theory
- Use theory progress to motivate new experiments with electrons
- Quantify “nuclear physics uncertainties” in ν-physics while learning nuclear structure

Nuclear structure theory

The ab-initio approach

- Start from protons and neutrons

- Solve the quantum mechanics of A=Z+N interacting nucleons

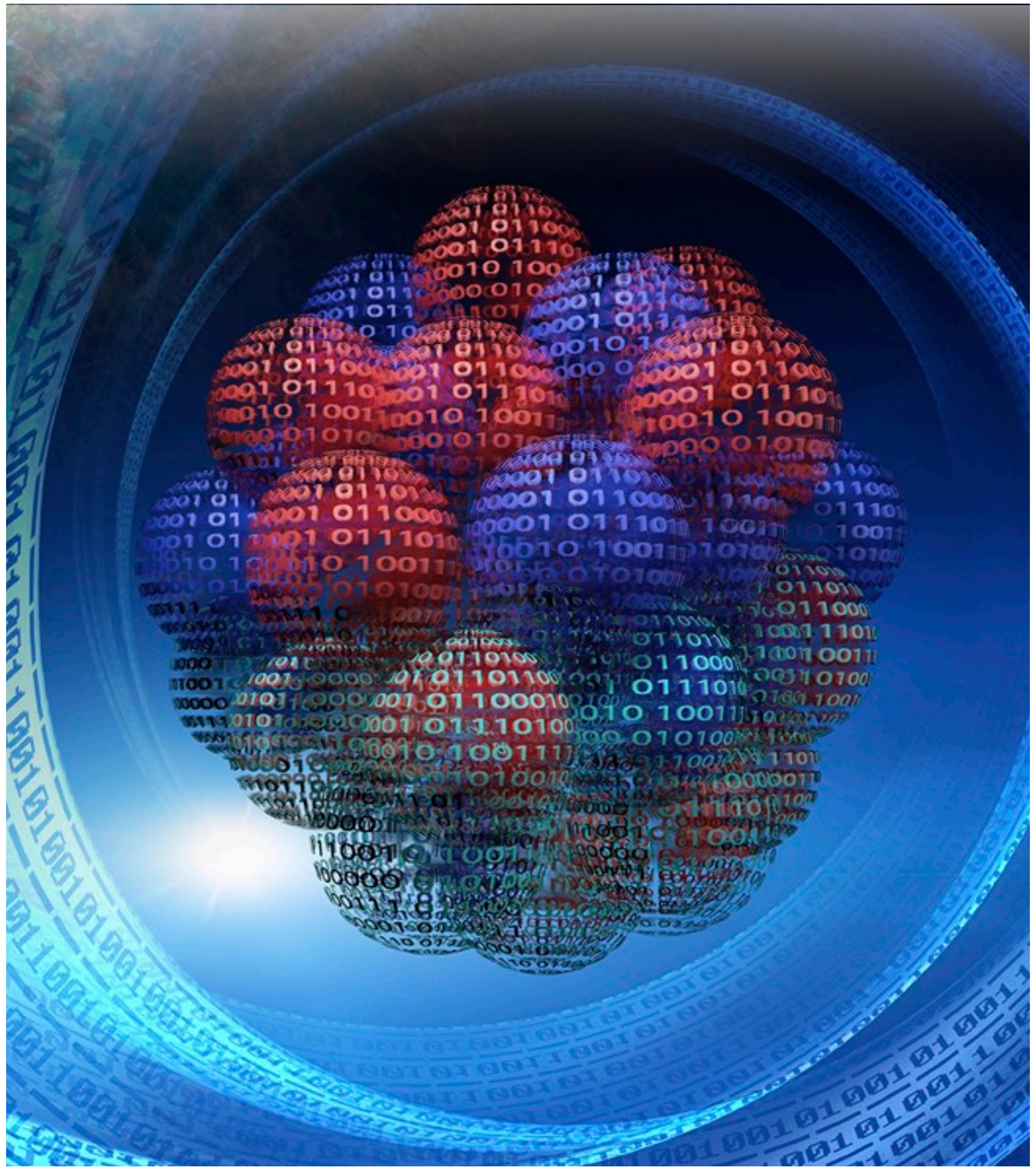
$$H|\Psi\rangle = E|\Psi\rangle$$

$$H = T + V$$

$$V = V_{NN} + V_{3N} + \ldots$$

from chiral effective field theory

- Find numerically solutions with controlled approximations and assess errors



Credits: ORNL, LeJean Hardin and Andy Sproles

Exciting times

Reaching heavier and heavier nuclear systems

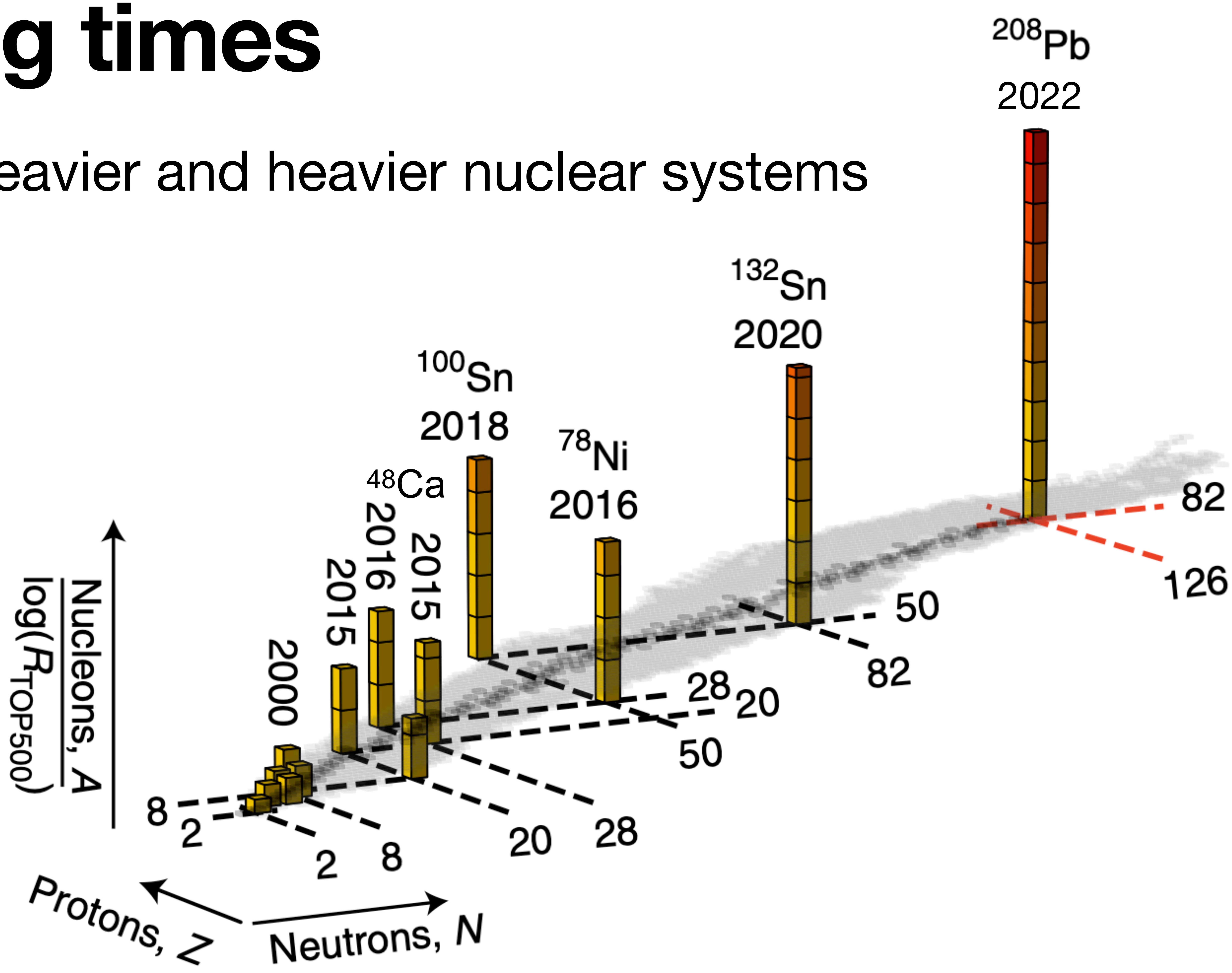


Fig. from B.Hu et al., Nature Phys. **18**, 1196 (2022)

How do we use ab-initio nuclear structure for neutrino physics?

1. Solve for the ground state
2. Calculate response functions

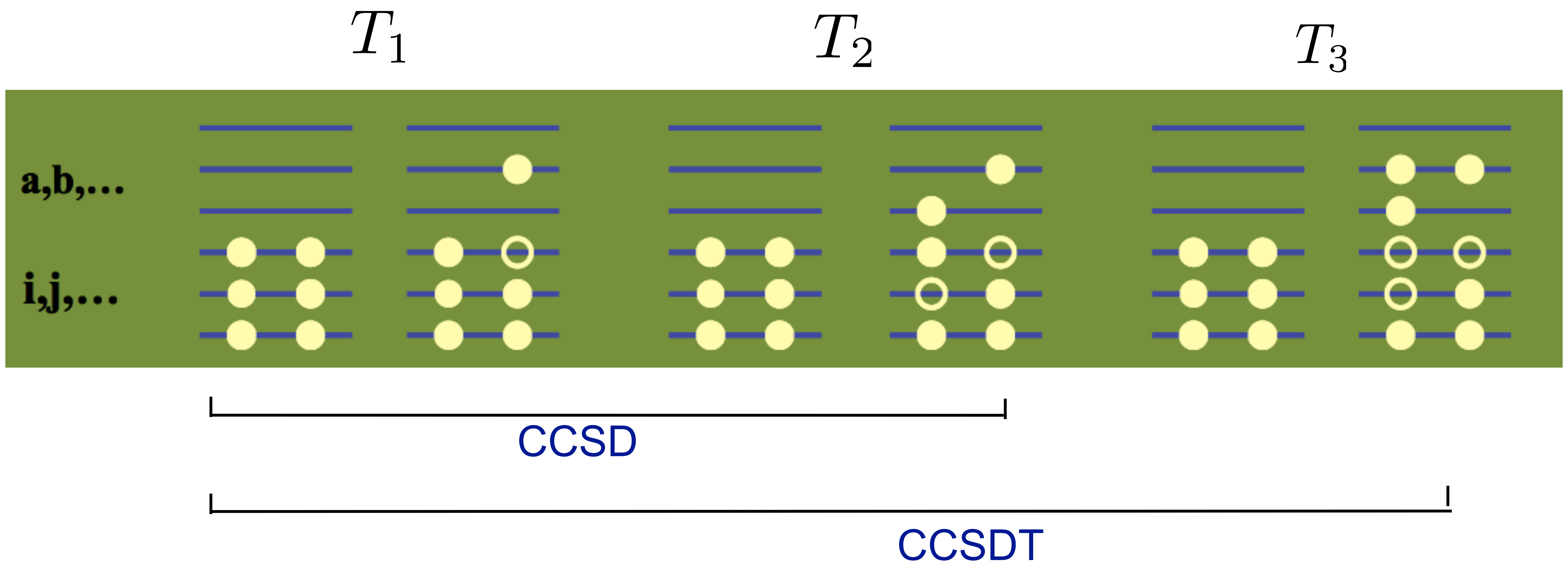
1. Solve for the ground state

Coupled-cluster theory

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

$$|\psi_0(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle = e^T |\phi_0(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle \qquad T = \sum T_{(A)}$$

cluster expansion



CCSD algorithm scales as $\sim A^6$

CEvNS from the standard model

C. Payne, SB et al., Phys. Rev. C 100, 061304(R) (2019)

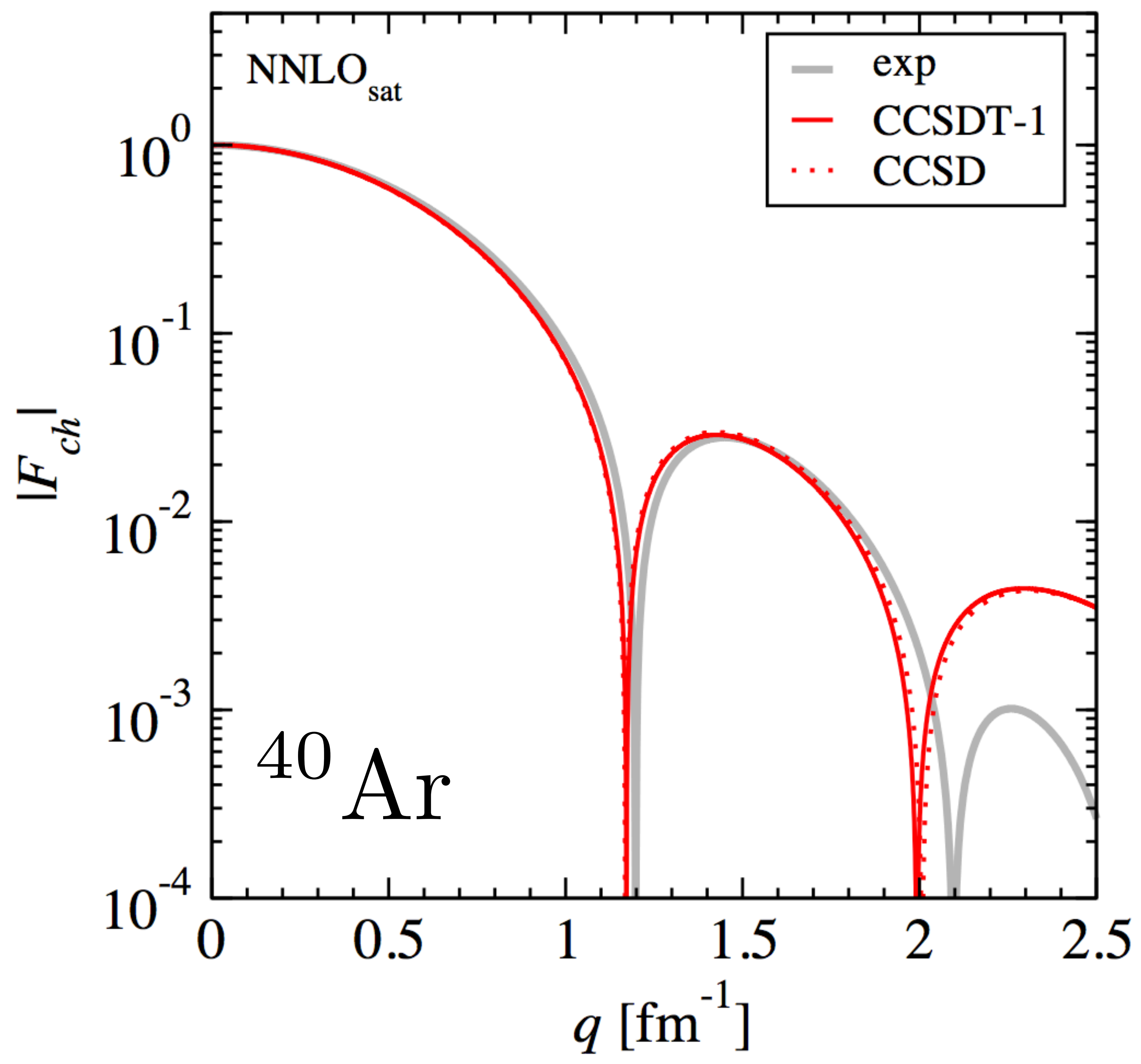
$$\frac{d\sigma}{dT}(E_\nu, T) \simeq \frac{G_F^2}{4\pi} M \left[1 - \frac{MT}{2E_\nu^2}\right] Q_W^2 F_W^2(q^2)$$

Weak charge

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

Weak form factor

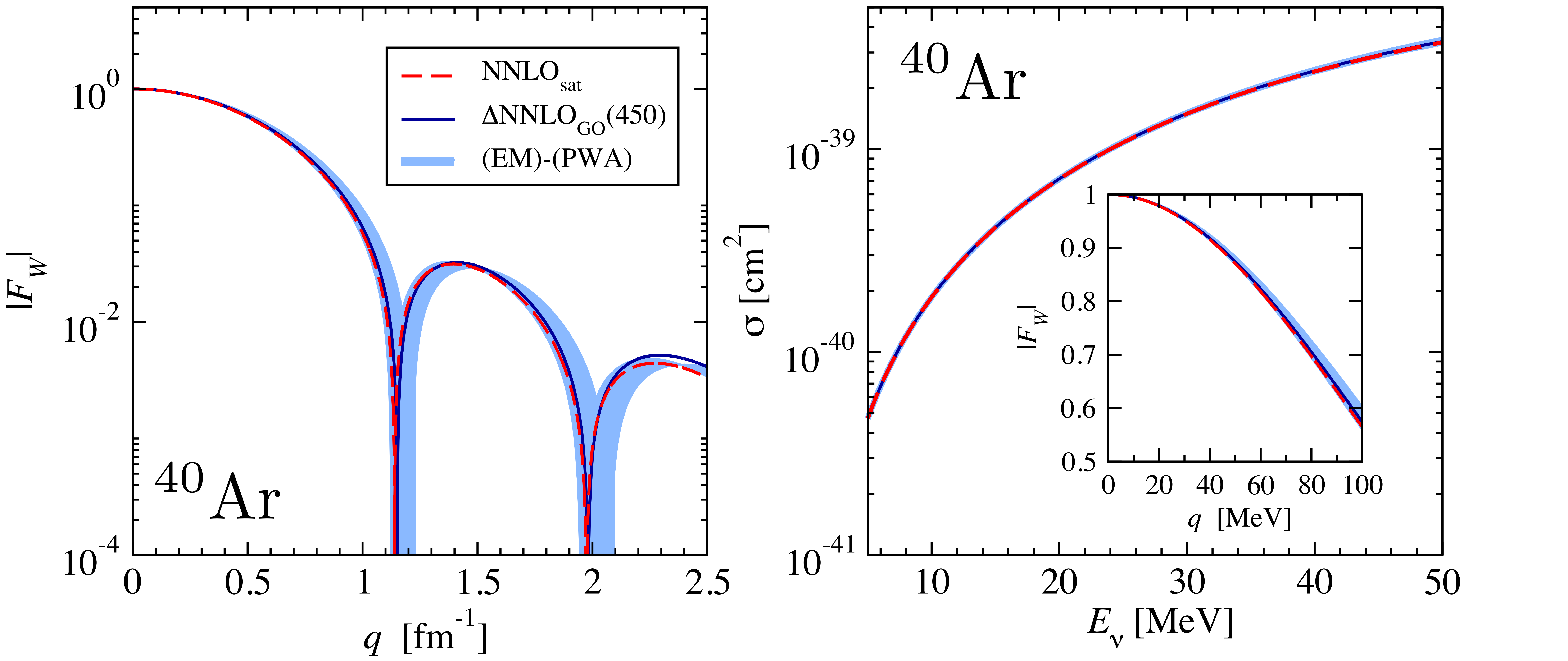
$$F_W(q^2) = \frac{1}{Q_W}\left[N F_n(q^2) - (1 - 4\sin^2\theta_W) Z F_p(q^2)\right]$$



exp: in Mainz, Ottermann et. al., Nucl. Phys. A **379**, 396 (1982)

CEvNS from the standard model

C. Payne, SB et al., Phys. Rev. C 100, 061304(R) (2019)



Small nuclear structure uncertainty in the cross section: 2% at q=50 MeV

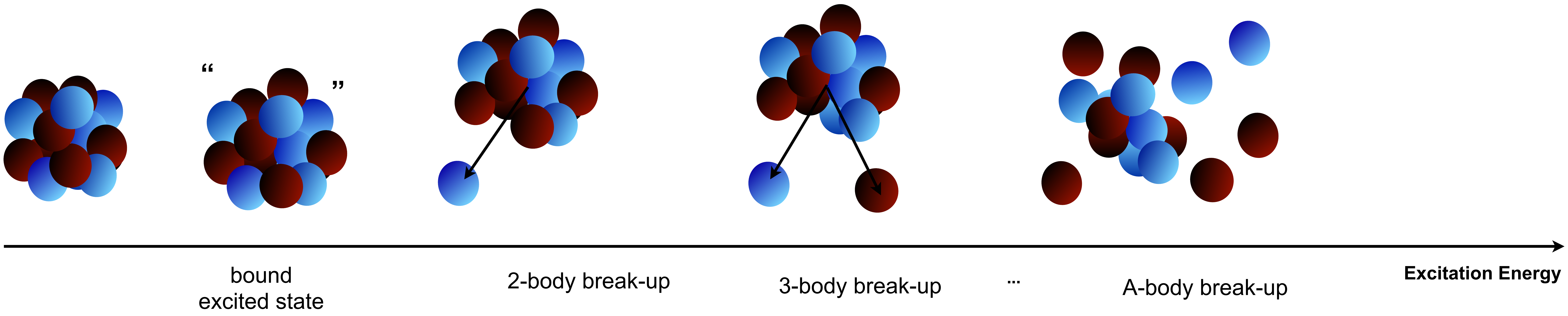
2. Calculate response functions

The 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

Exact knowledge limited

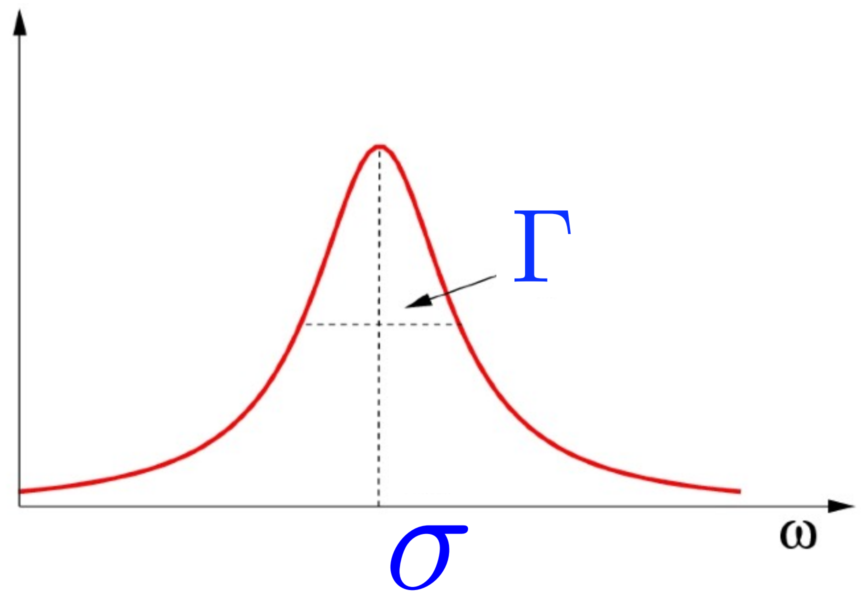


Lorentz Integral Transform

Efros, *et al.*, JPG.: Nucl.Part.Phys. **34** (2007) R459

inversion

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



Reduce to a bound-state-like equation

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

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

LIT-CC

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

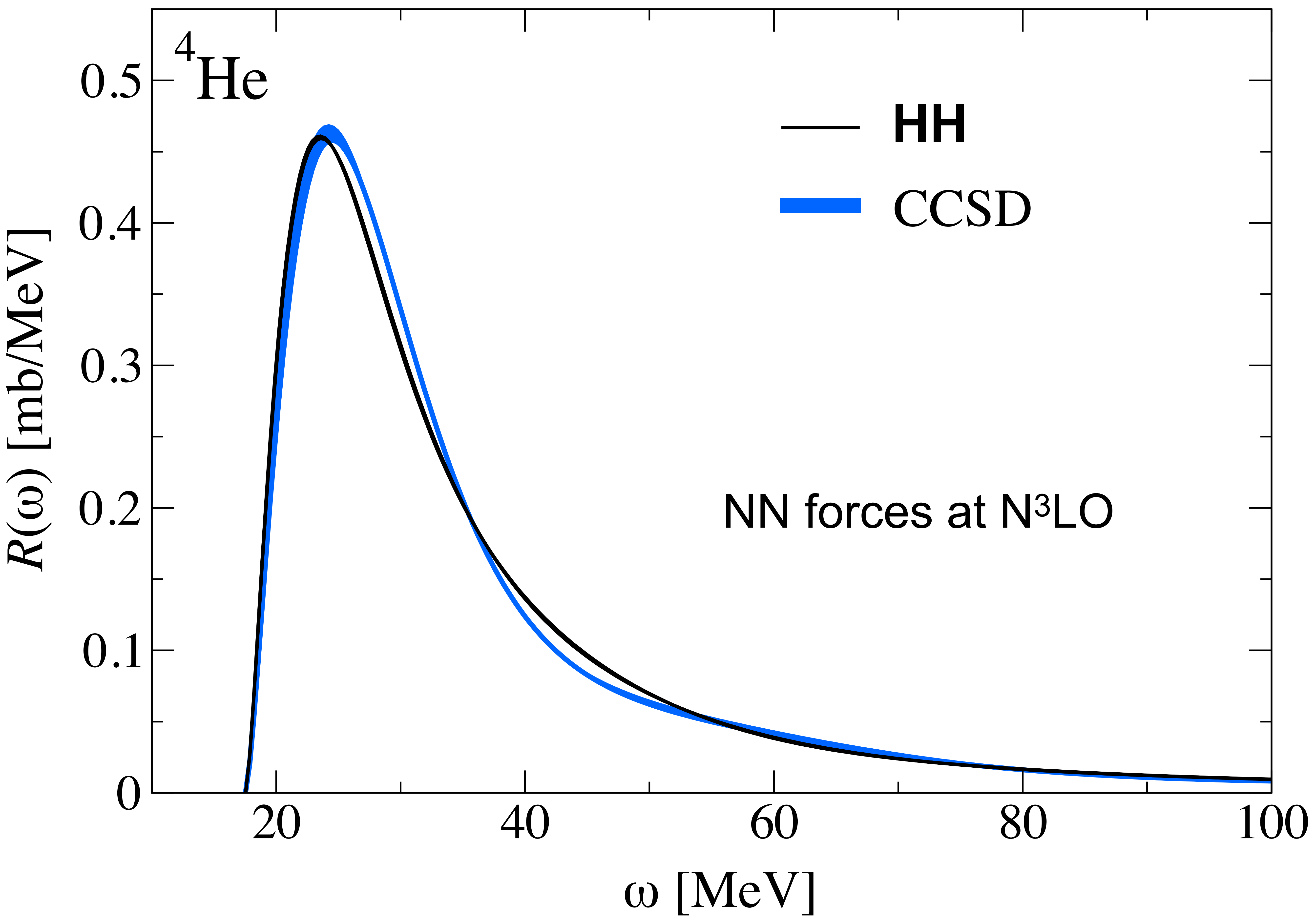
$$\bar{H} = e^{-T}He^{T}$$

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

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

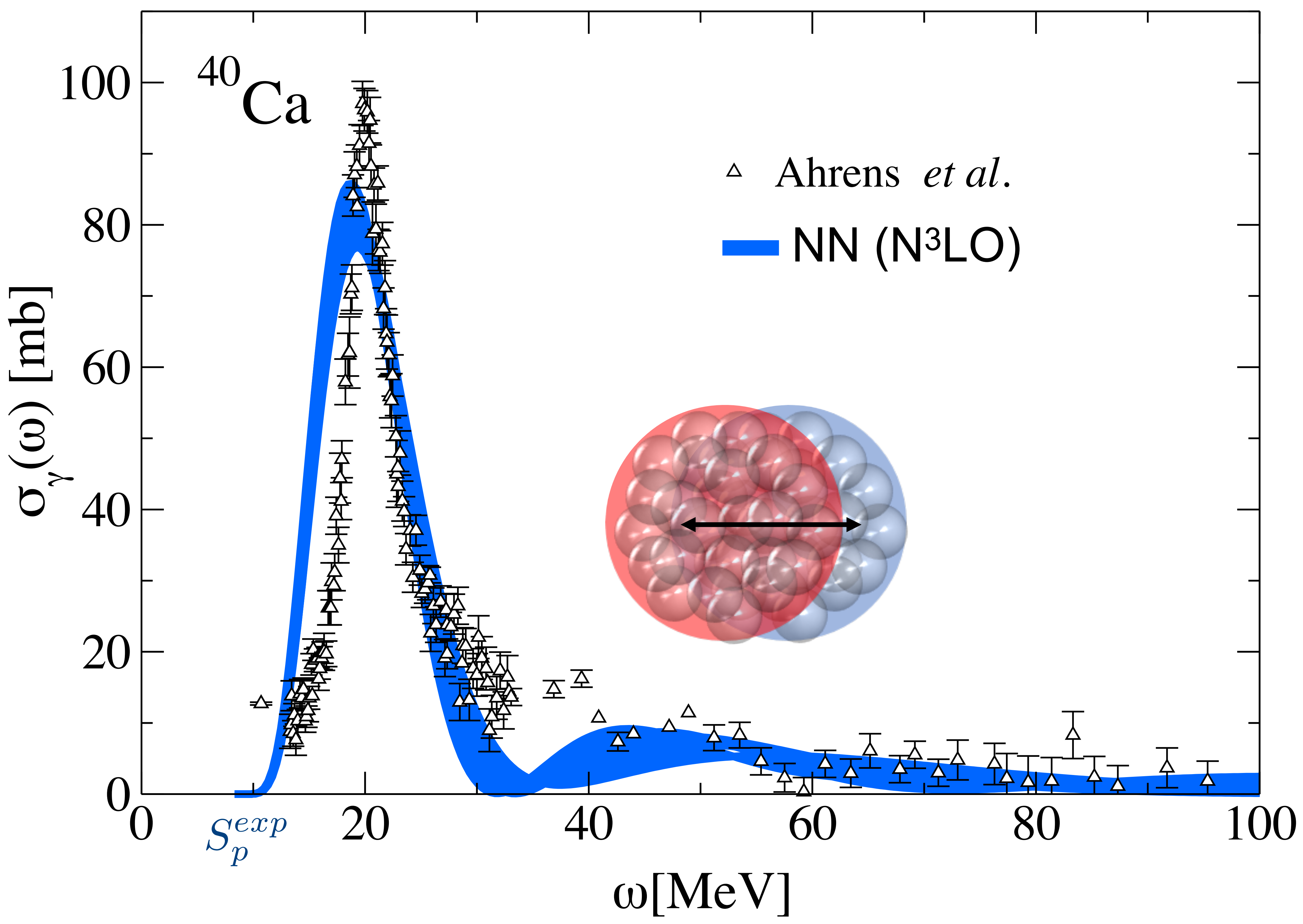
CC formulation of LIT: benchmark on ^{4}He

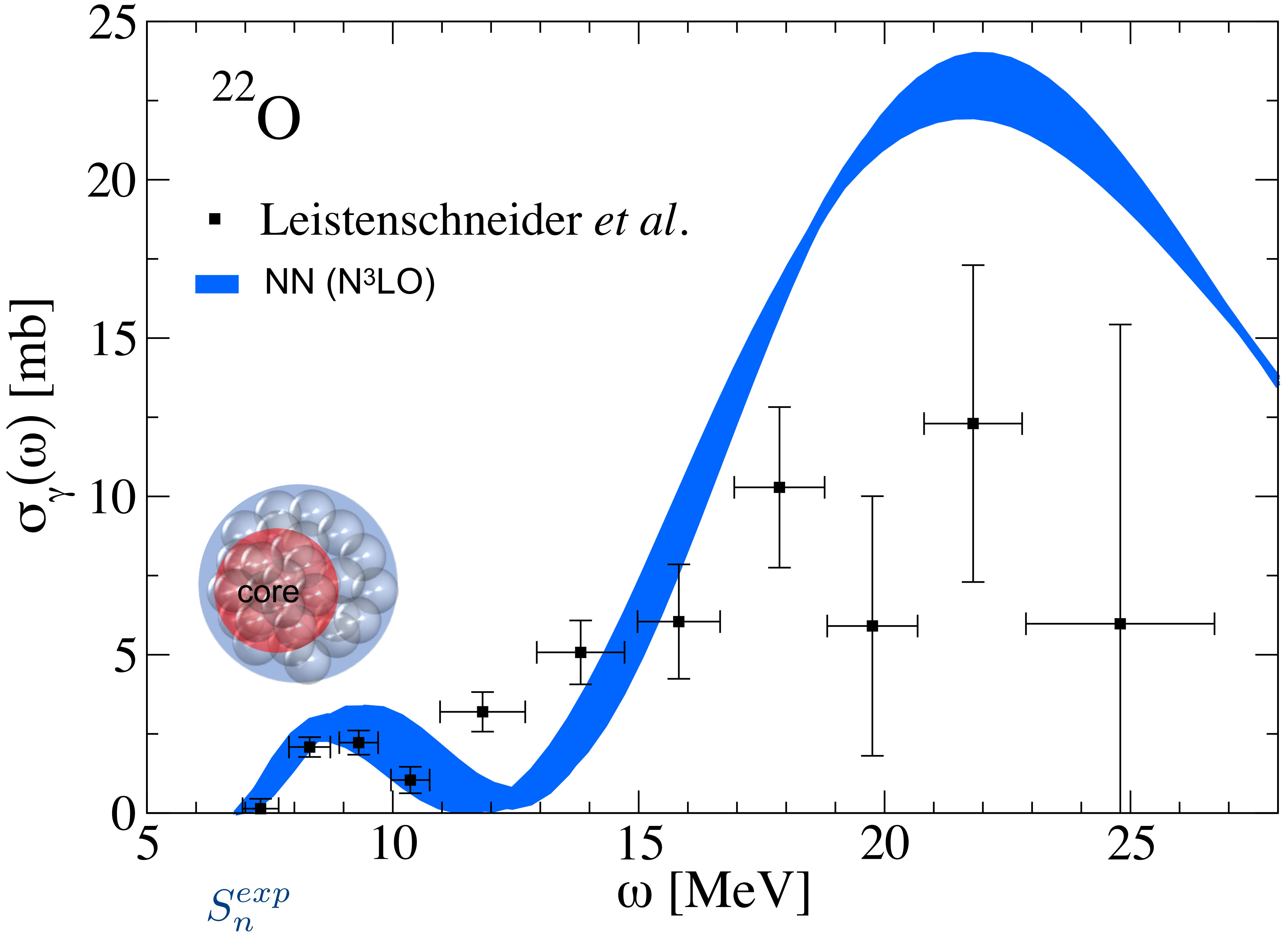
SB et al., Phys. Rev. Lett. 111, 122502 (2013)



Medium-mass nuclei

SB et al., PRC 90, 064619 (2014)



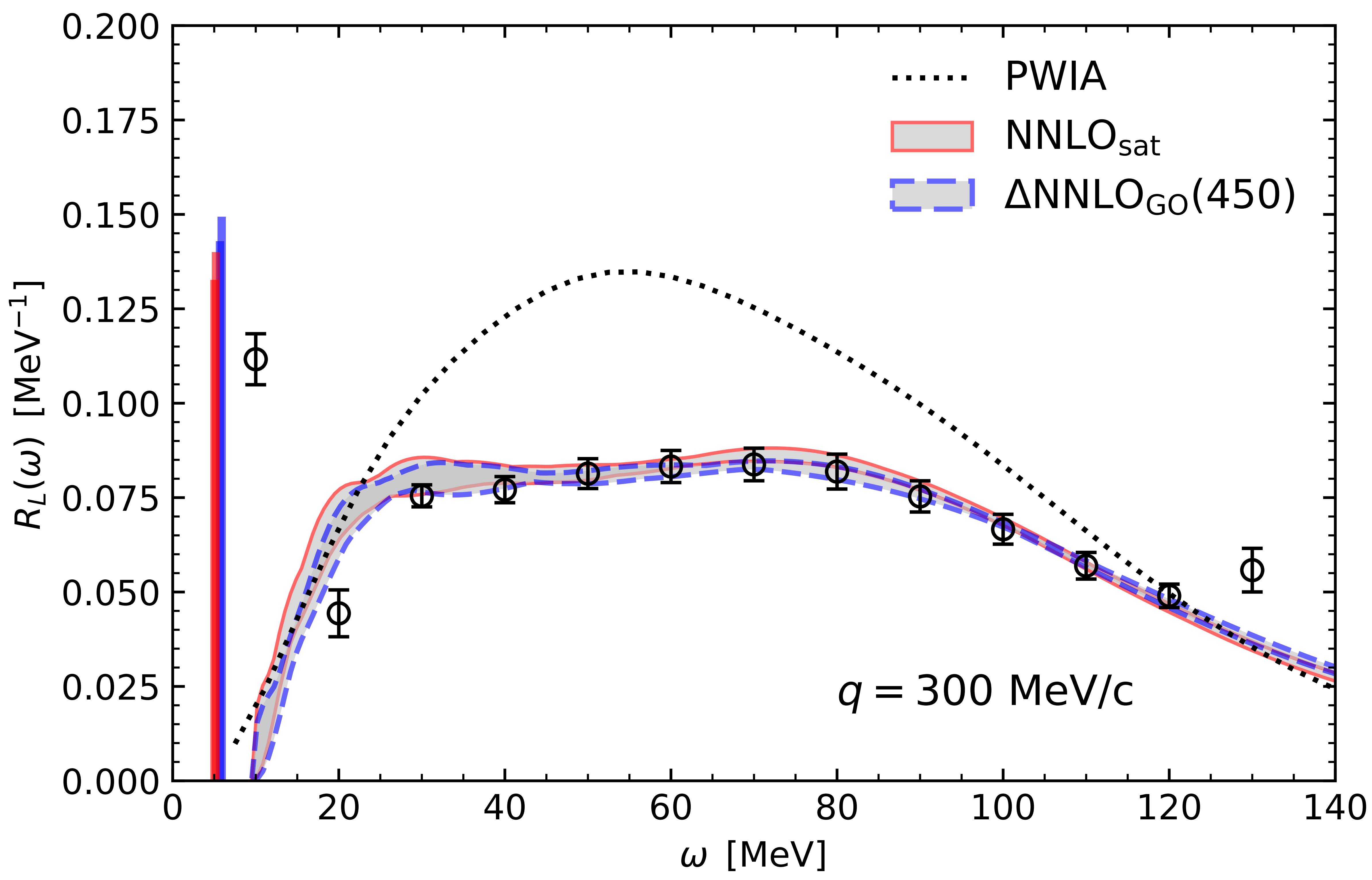


Applications to lepton-nucleus scattering

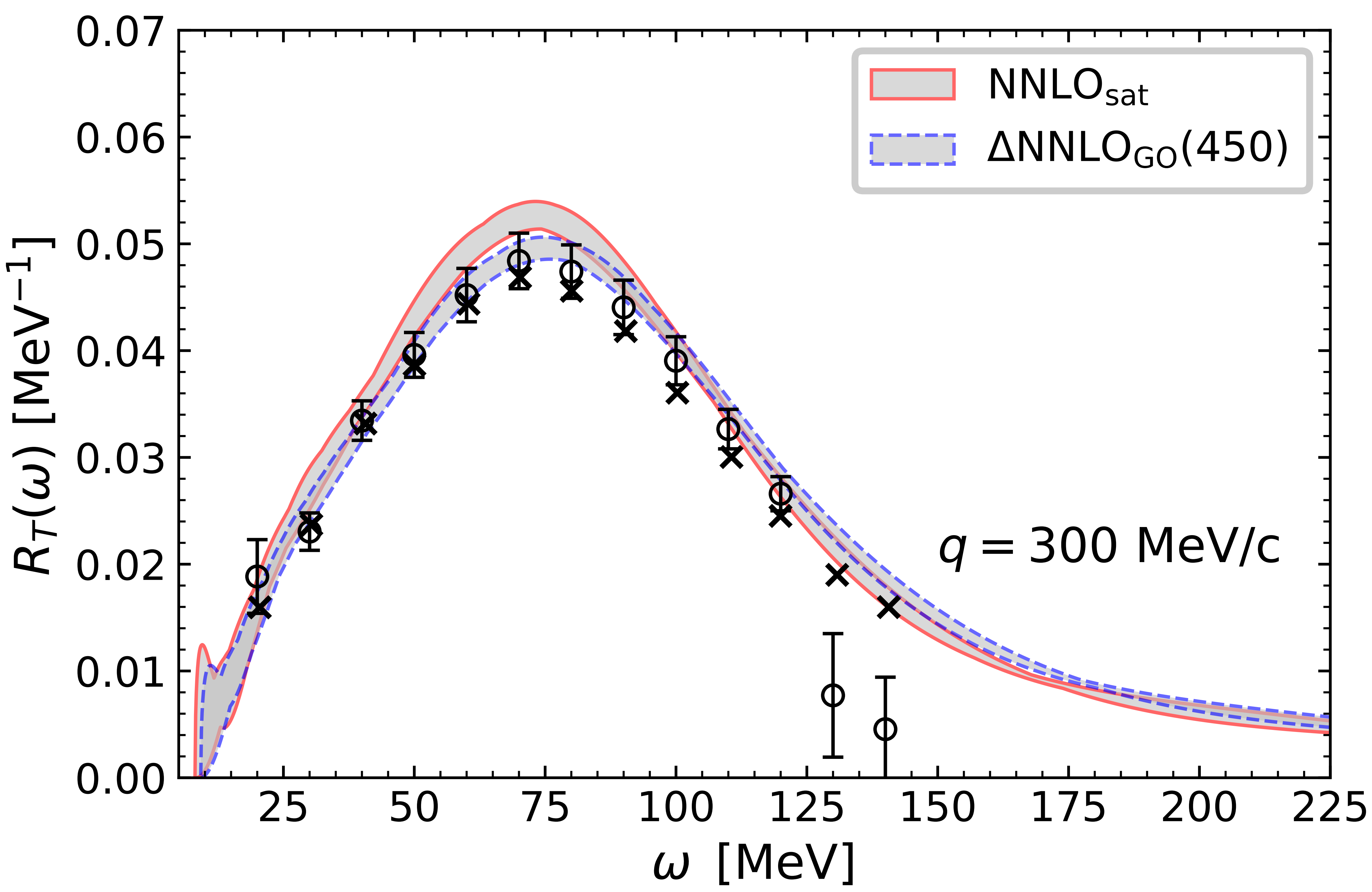
Electron scattering with LIT-CC

$^{40}Ca(e,e')X$

Sobcyzk, Acharya, SB, Hagen, PRL 127 (2021) 7, 072501



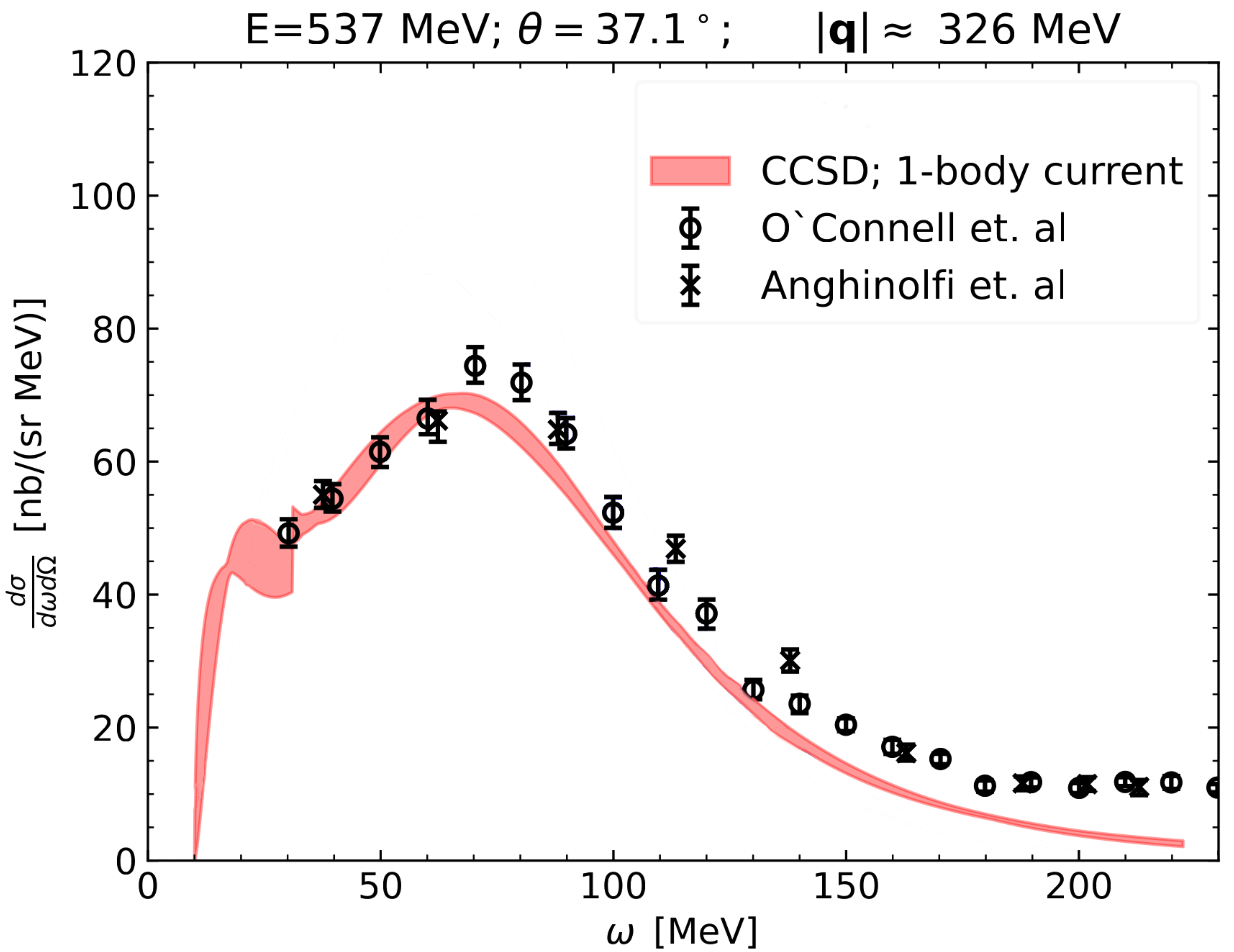
Sobczyk, Acharya, SB, G. Hagen, PRC 109 (2024) 2, 025502



Electron scattering with LIT-CC

$^{16}O(e,e')X$

Acharya, Sobczyk, SB, et al. aXiv:2410.05962, to appear on PRL



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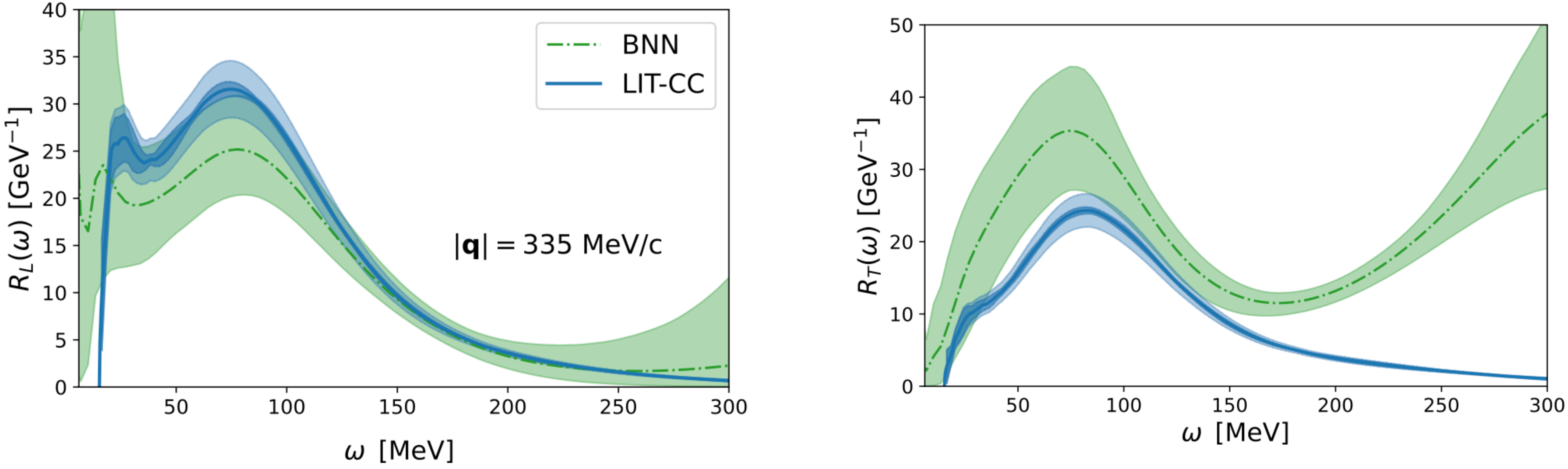
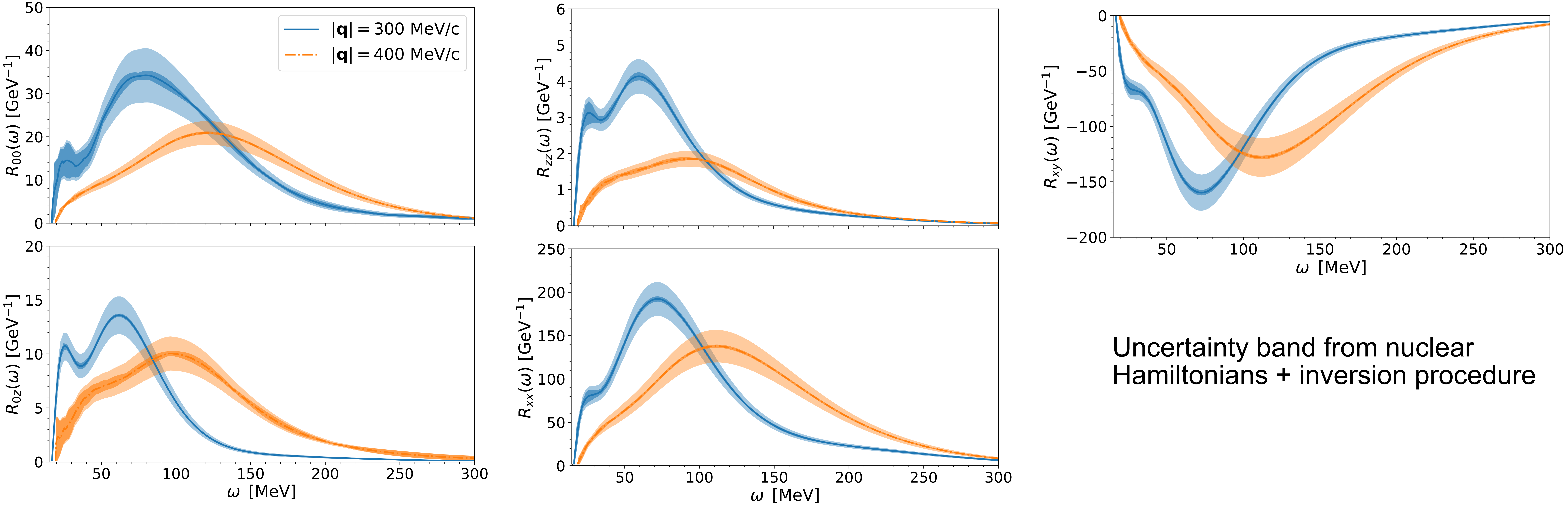


BNN from Sobczyk, Rocco, Lovato, Phys. Lett. B 859 (2024) 139142

Towards neutrino scattering with LIT-CC: ^{16}O

Acharya, Sobczyk, SB, et al. aXiv:2410.05962, to appear on PRL

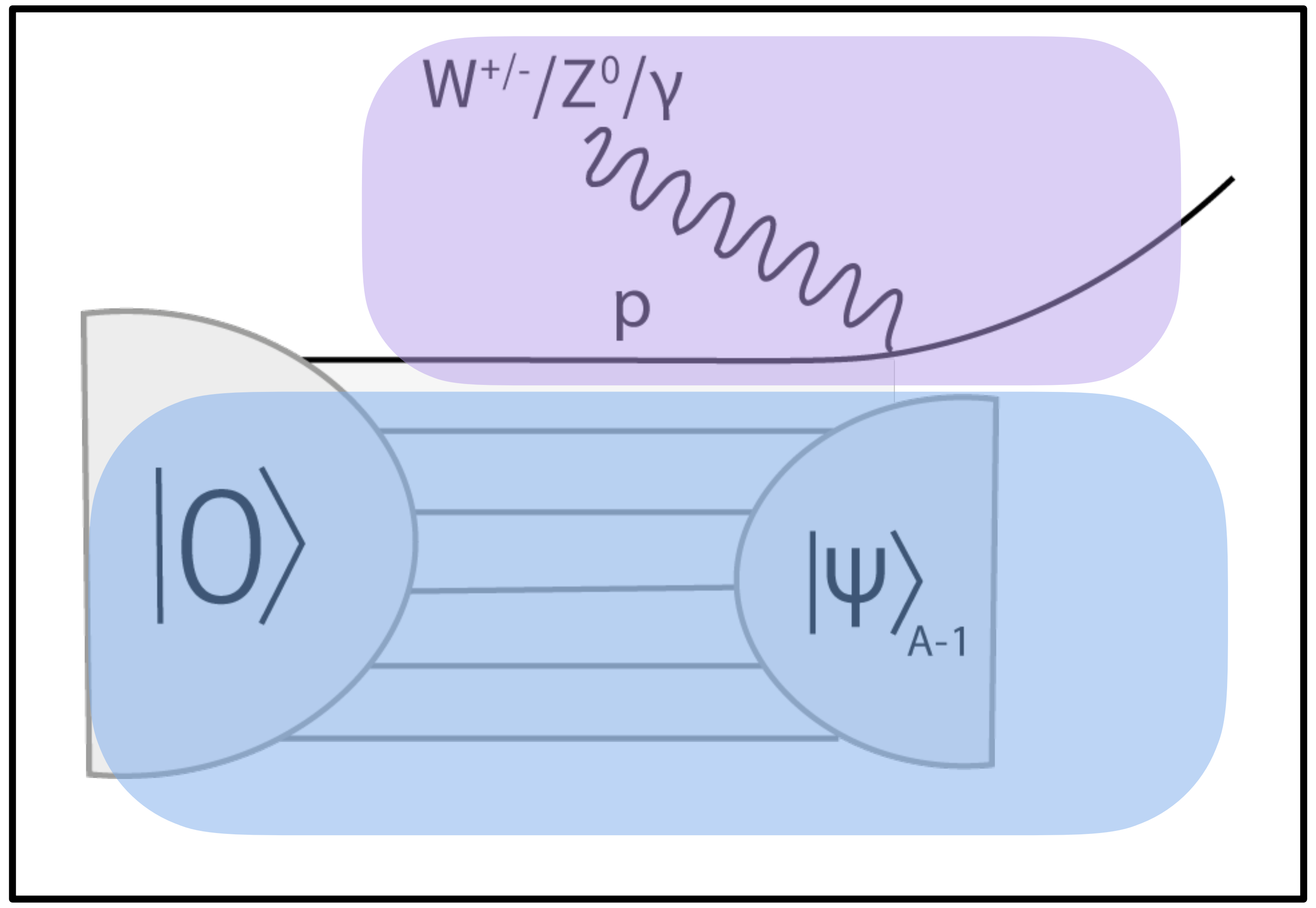
$$\left.\frac{d\sigma}{dE'd\Omega}\right|_{\nu/\bar{\nu}} = \sigma_0\Big(v_{00}R_{00} + v_{0z}R_{0z} + v_{zz}R_{zz} + v_T R_T \pm v_{xy}R_{xy}\Big)$$



Uncertainty band from nuclear Hamiltonians + inversion procedure

What about higher energies?

Spectral function formalism



$$\sigma \propto |\mathscr{M}|^2 S(E,p)$$

Factorized interaction vertex
(relativistic, pion production…)

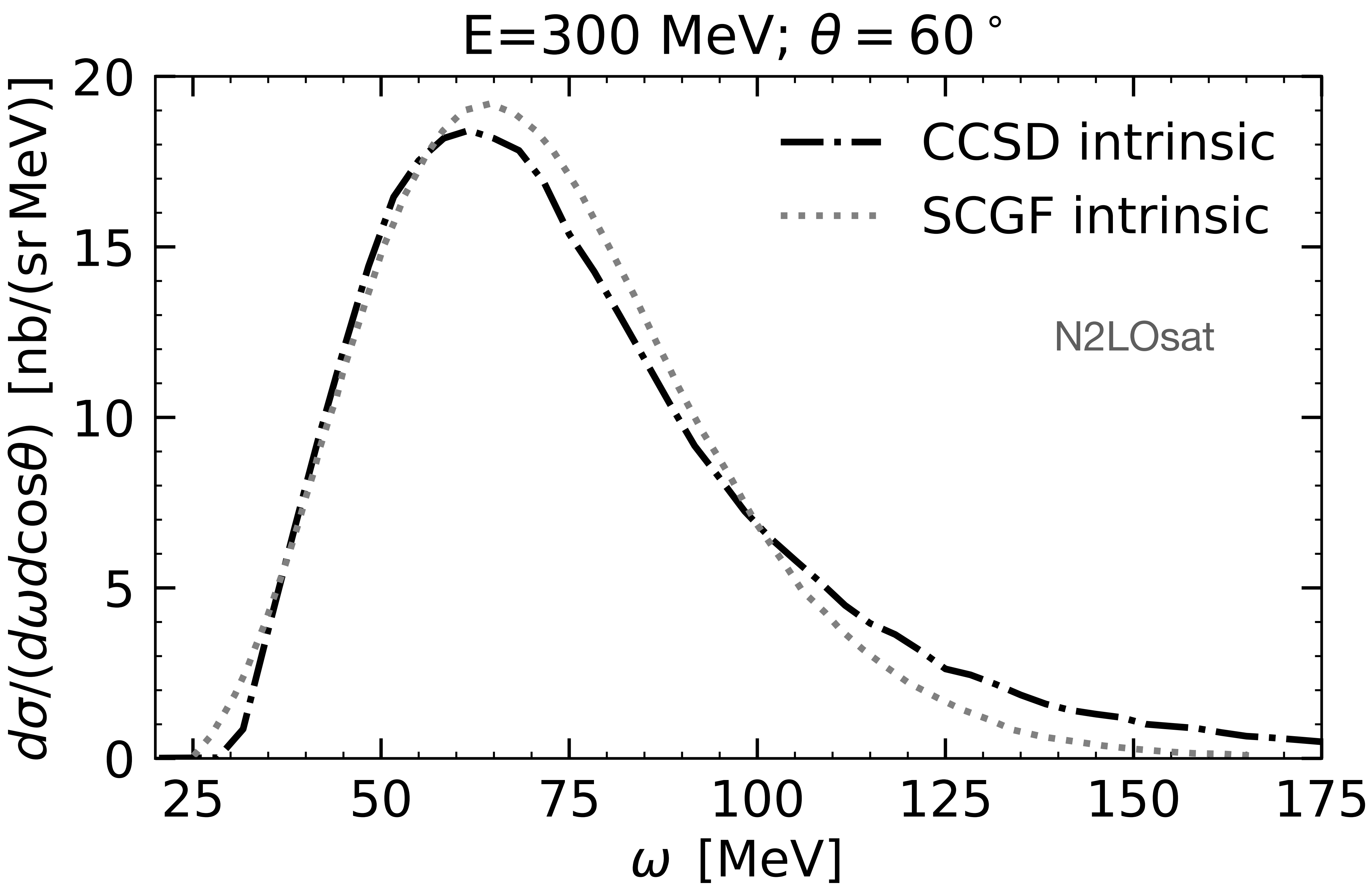
Spectral function

Probability of finding nucleon with $(E, \mathbf{p})$ *in nuclear ground state*

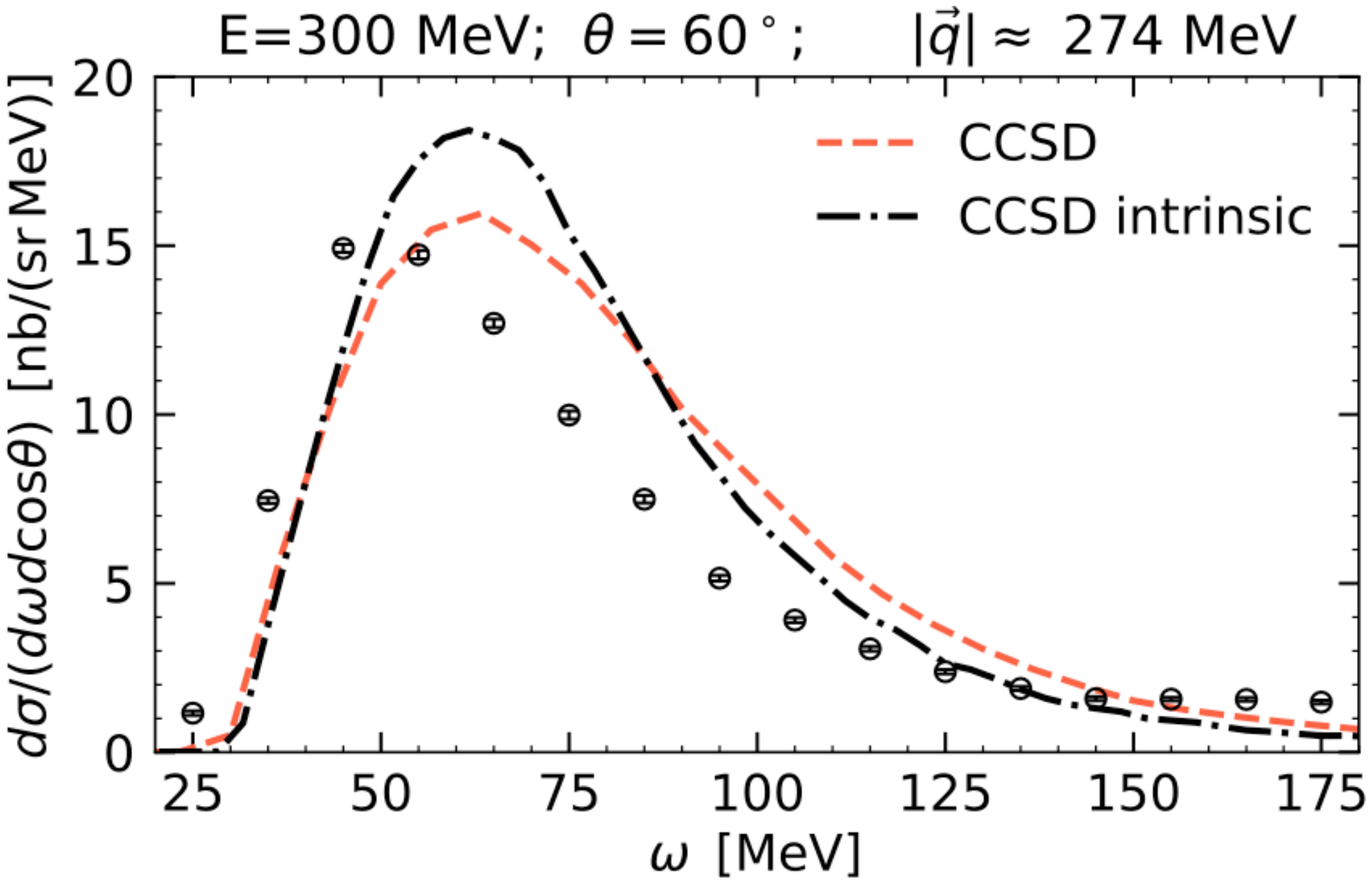
S$(E, \mathbf{p})$ calculated with CC theory using the Chebyshev method
→ **see talk by Immo Reis next week**

Spectral function formalism for ^{4}He

Sobczyk, SB, et al., PRC 106, 034310(2022)

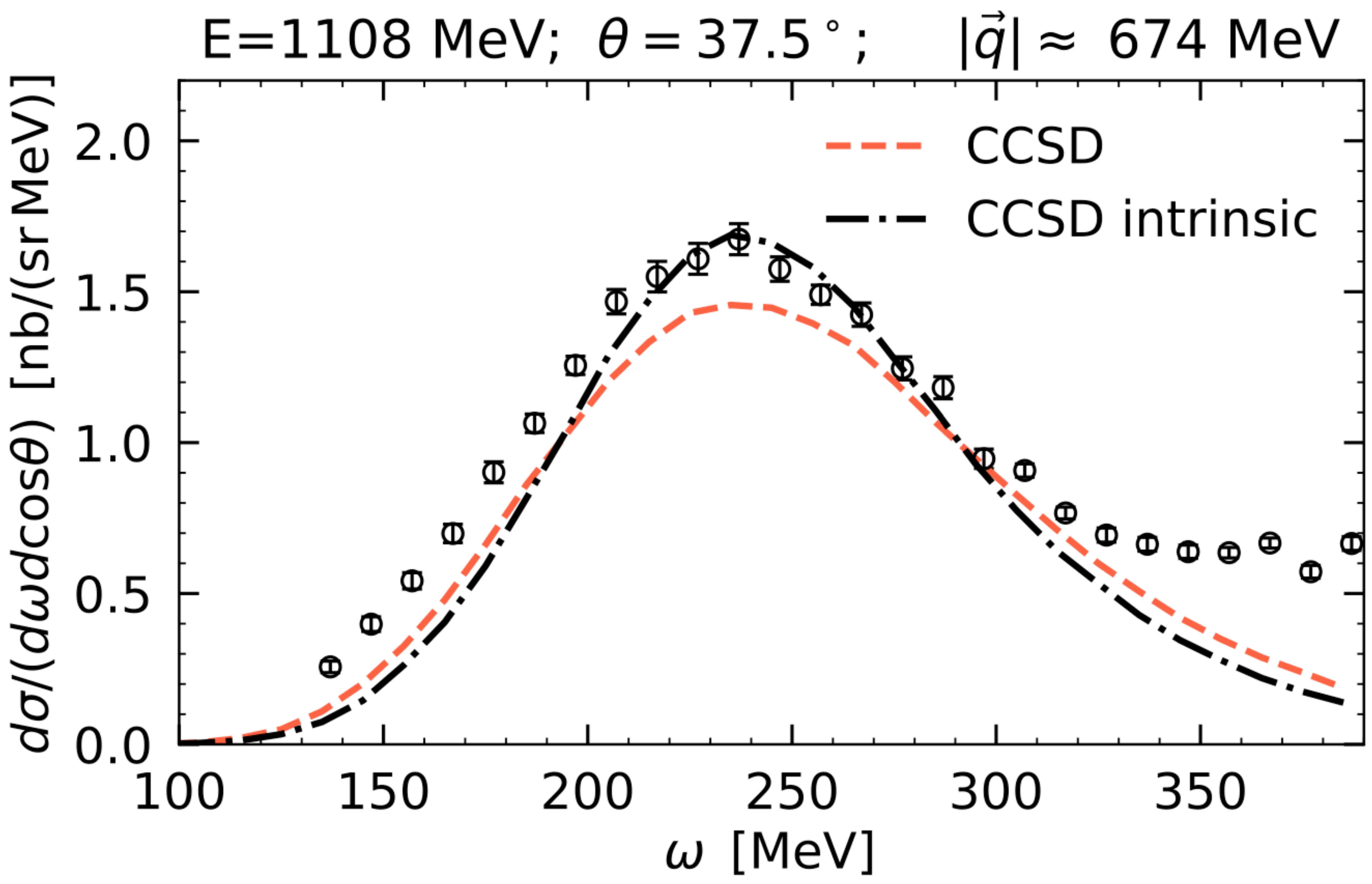


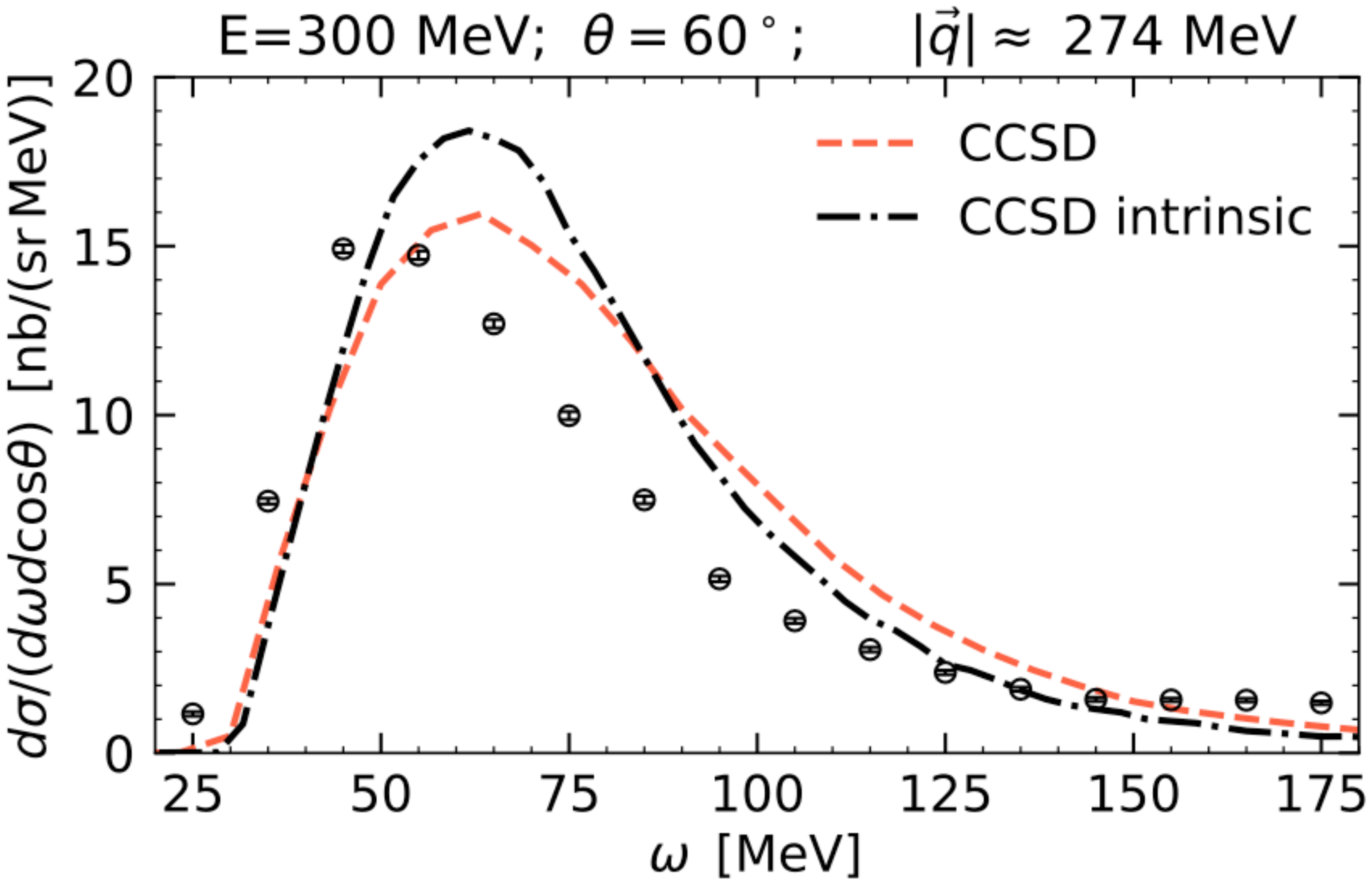
SCGF: Rocco, Barbieri, PRC 98 (2018) 022501



Spectral function formalism for ^{4}He

Sobczyk, SB, et al., PRC 106, 034310(2022)





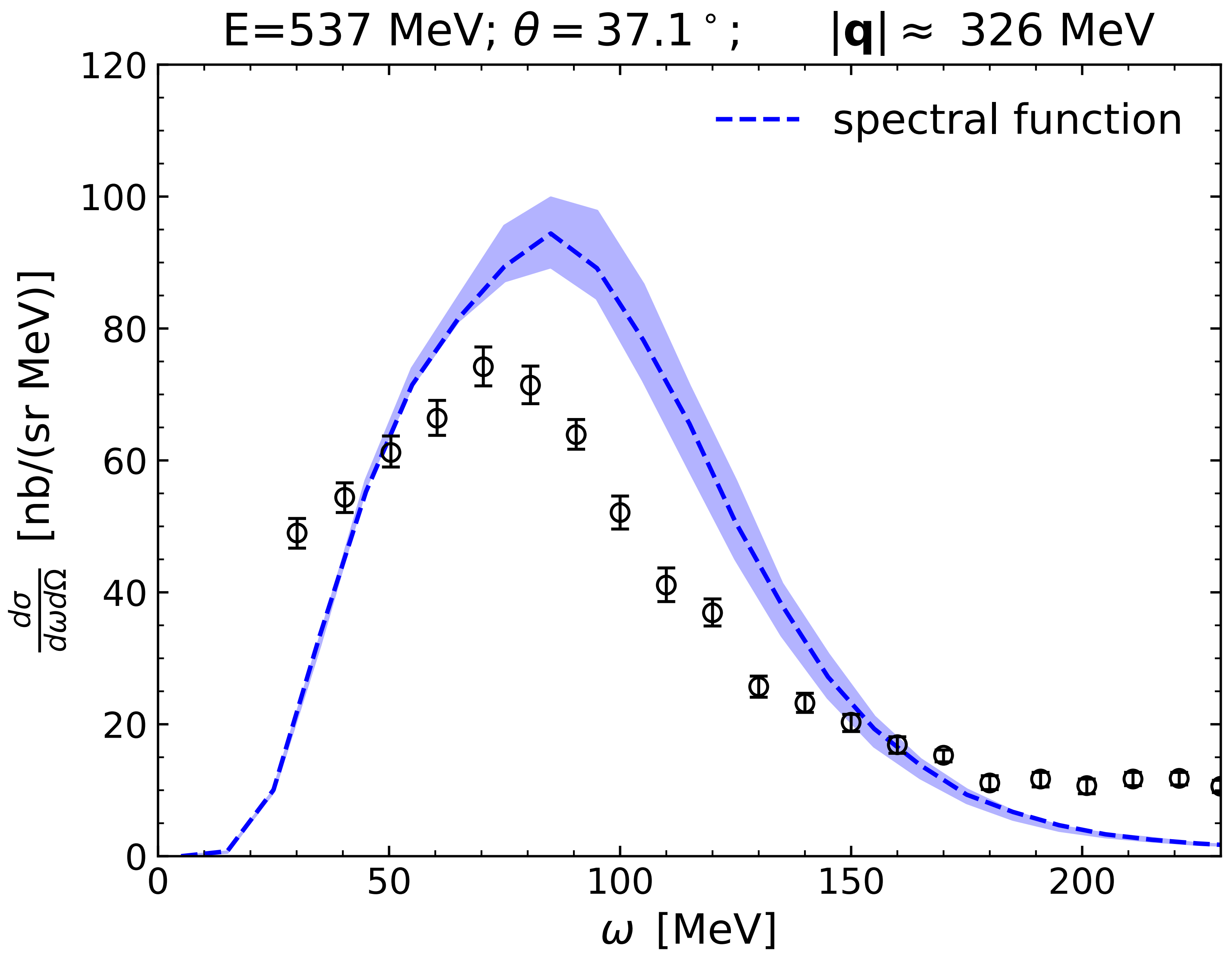
SF works at high-energy/high-momentum

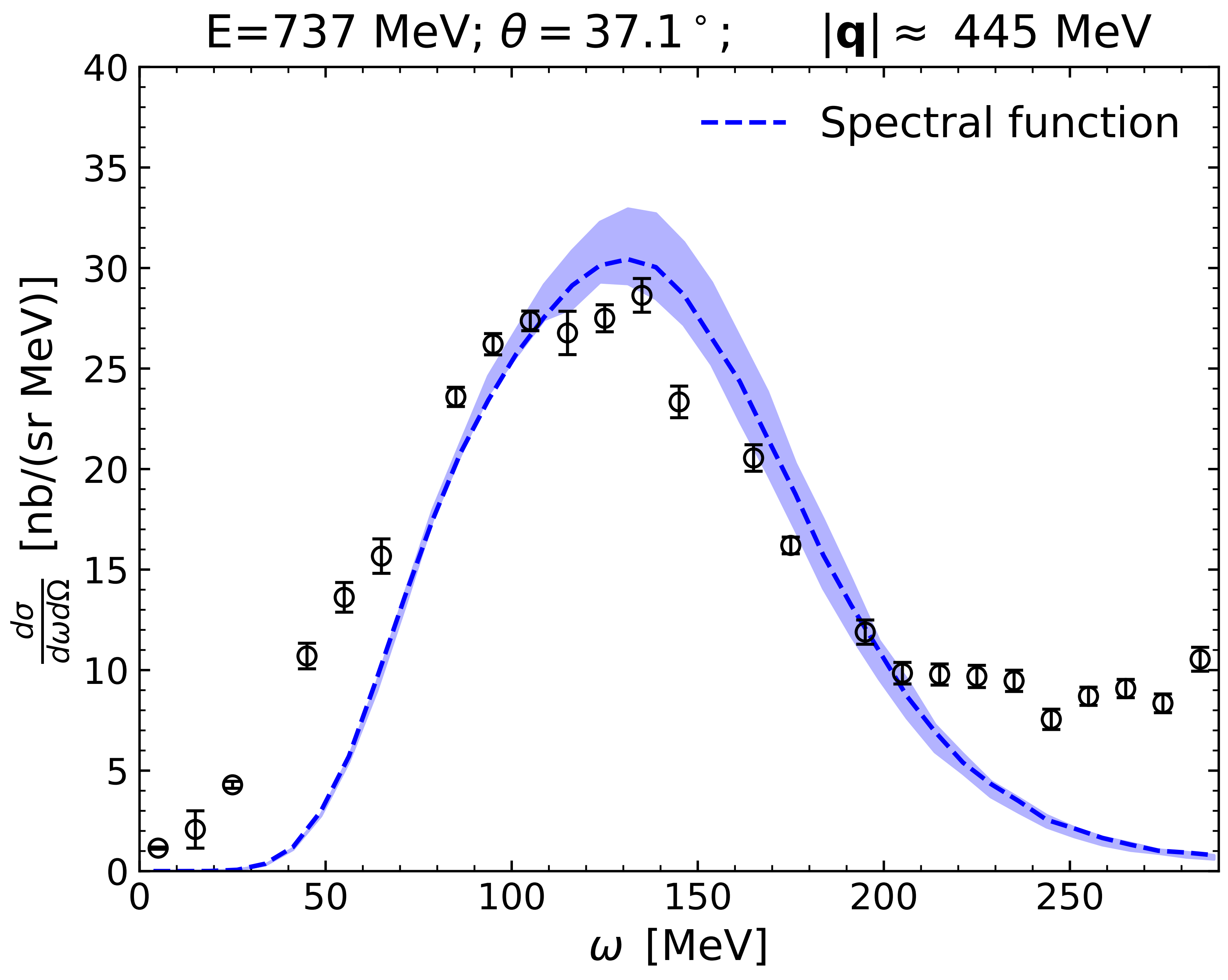
Spectral function formalism for ^{16}O

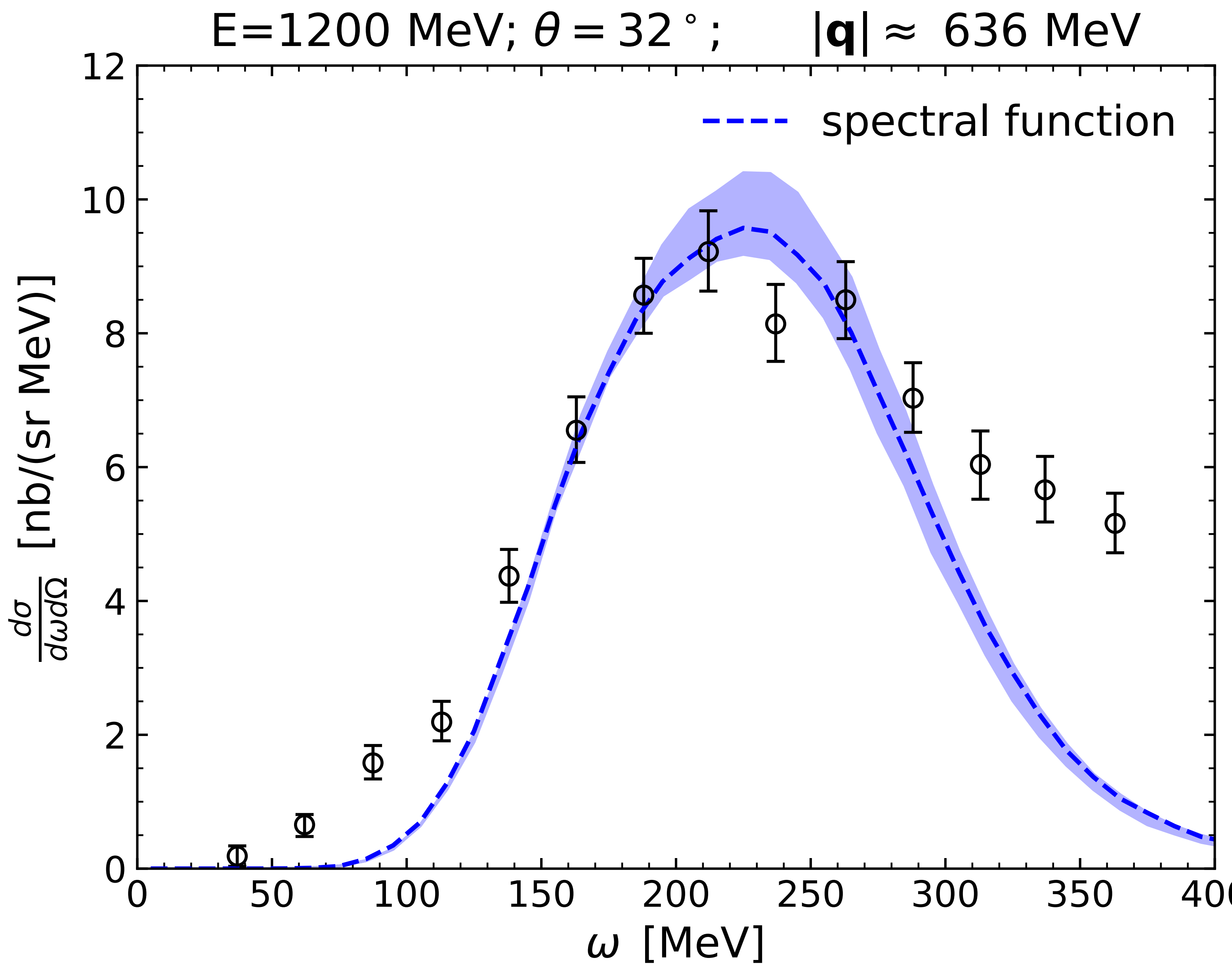
$$e + {}^{16}\mathrm{O} \rightarrow e' + X$$

Sobczyk, SB, PRC 109, 044314 (2024)

growing **q** momentum transfer → final state interactions play minor role







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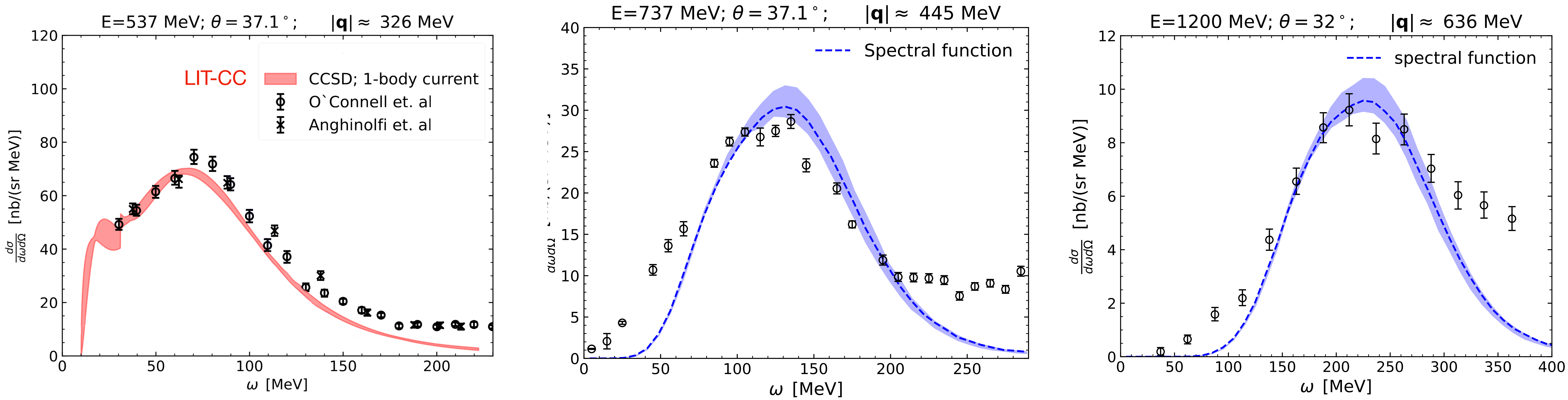
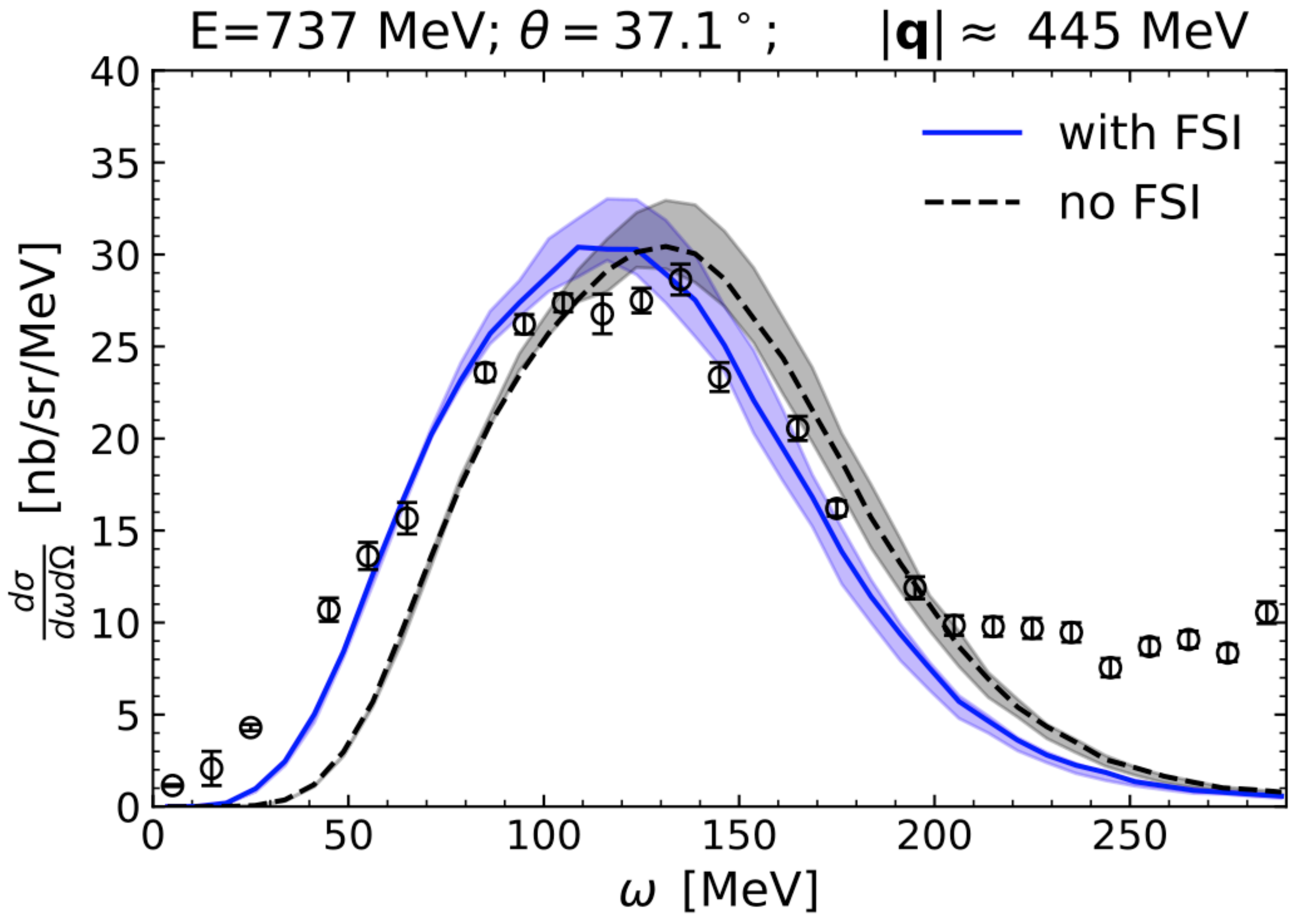


LIT-CC works at low-energy/low-momentum

FSI for ^{16}O from optical potential

$$e + {}^{16}\mathrm{O} \rightarrow e' + X$$

Sobczyk, SB, PRC 109, 044314 (2024)

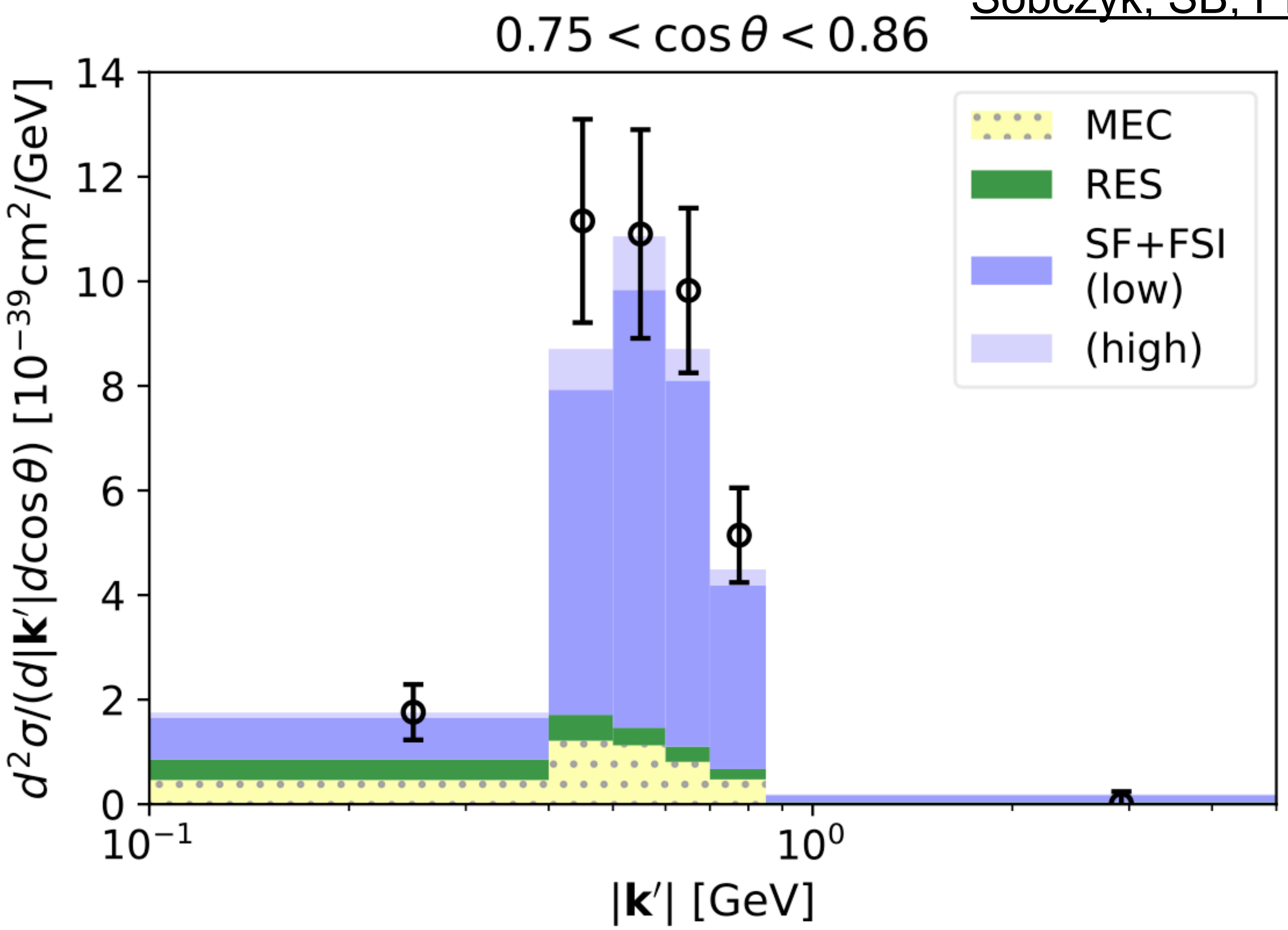


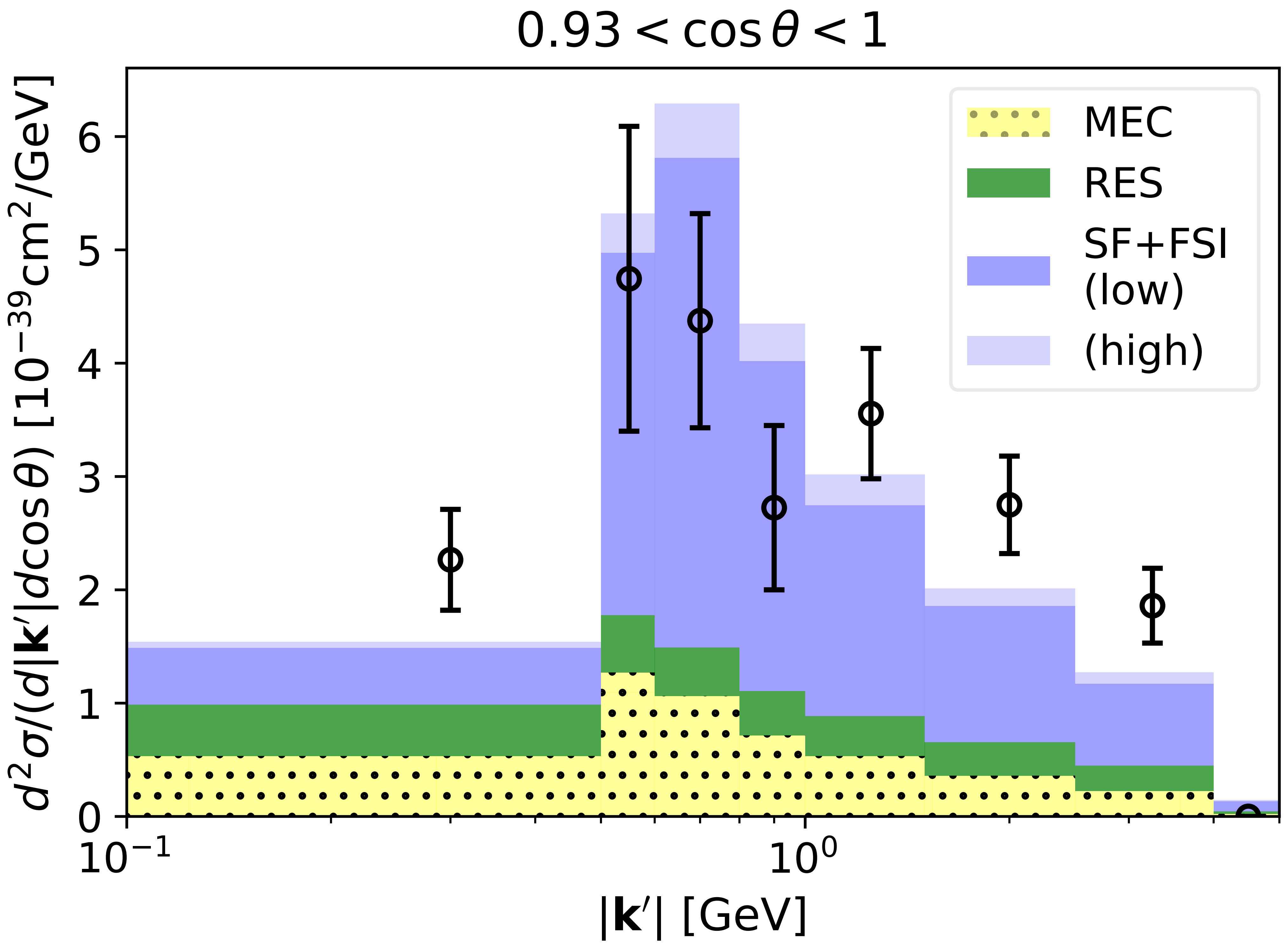
Towards neutrino scattering: T2K data

With ab initio Spectral function

$$\nu_\mu + {}^{16}\mathrm{O} \rightarrow \mu^- + X$$

Sobczyk, SB, PRC 109, 044314 (2024)

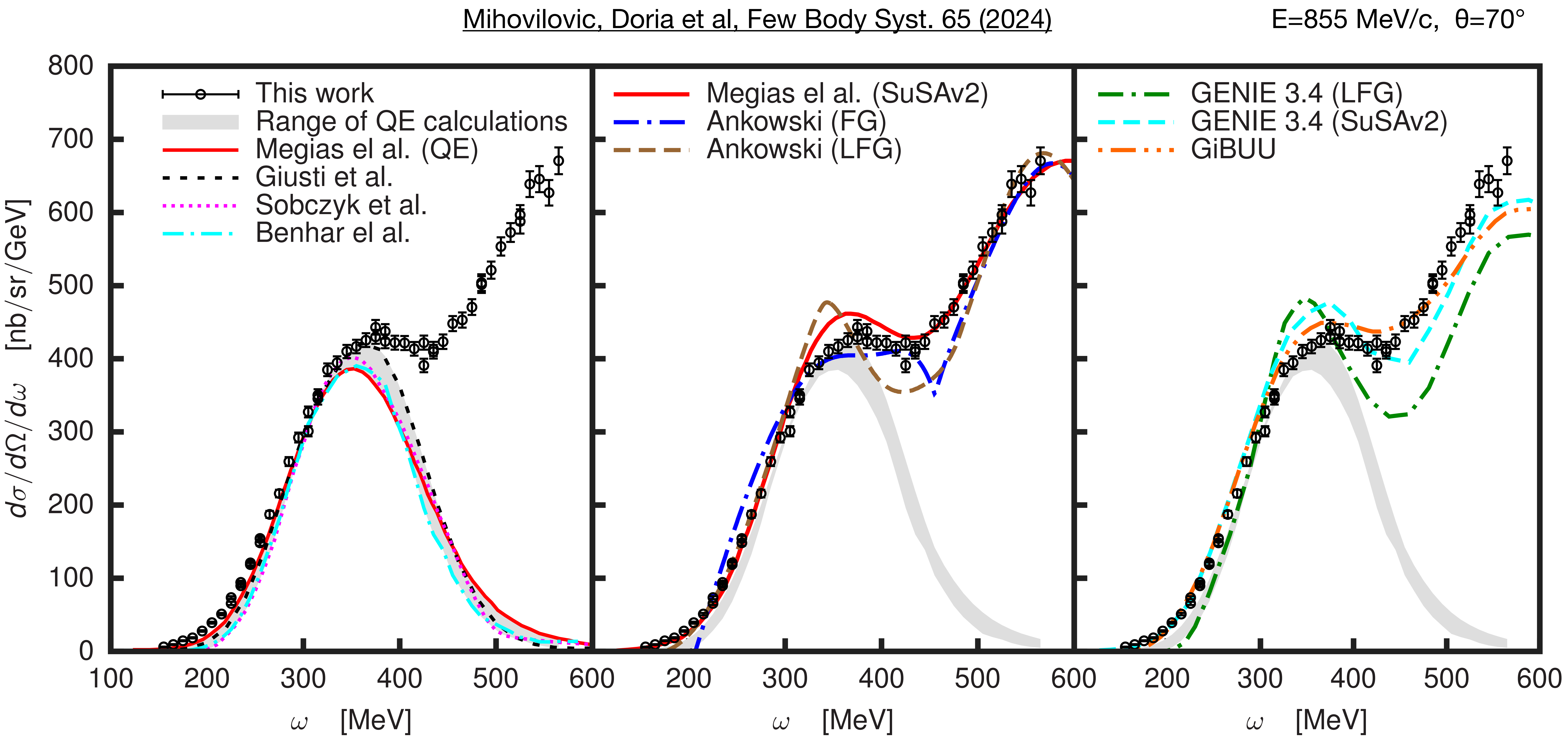




see talk by Immo Reis next week

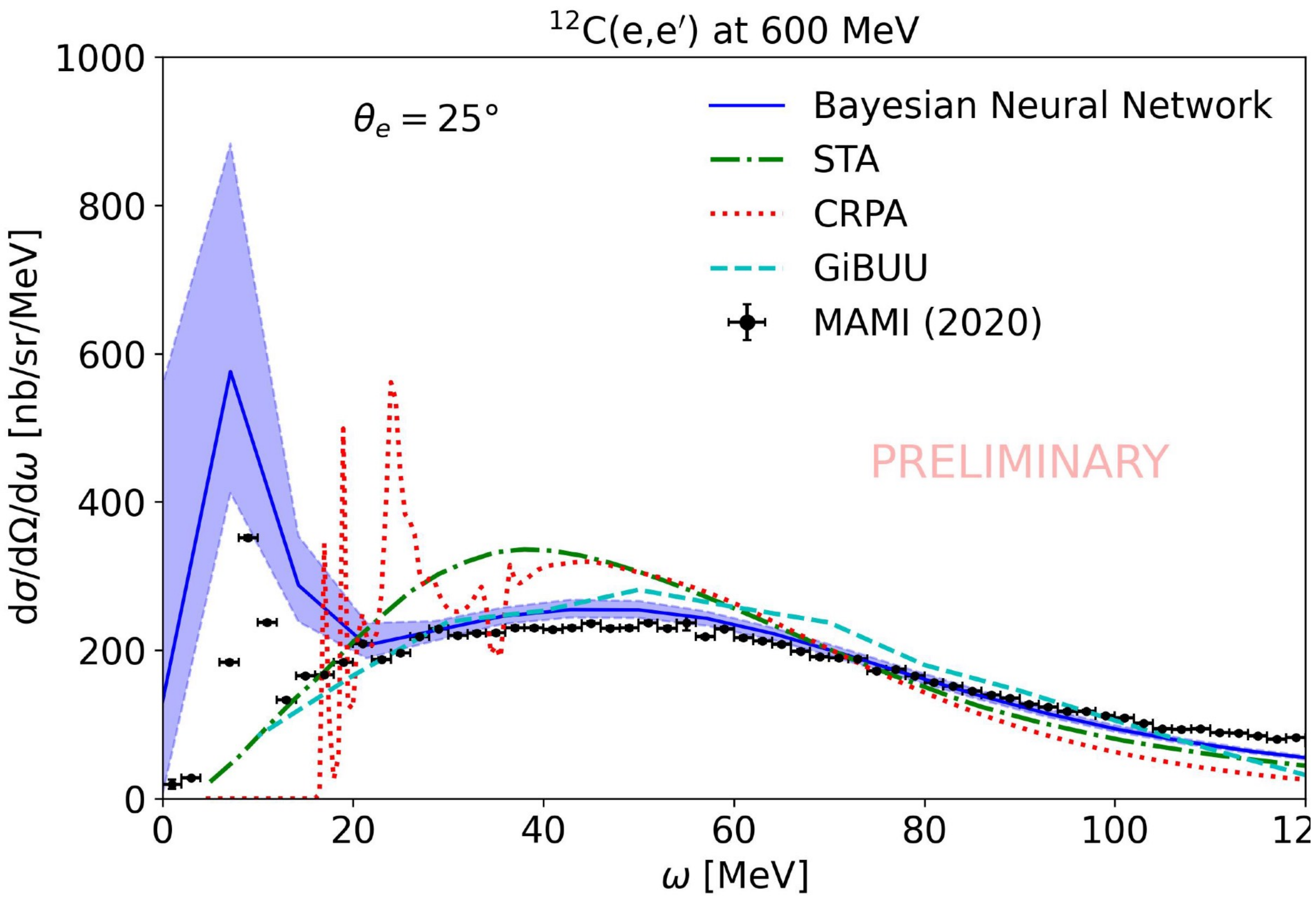
e4ν experiments in Mainz

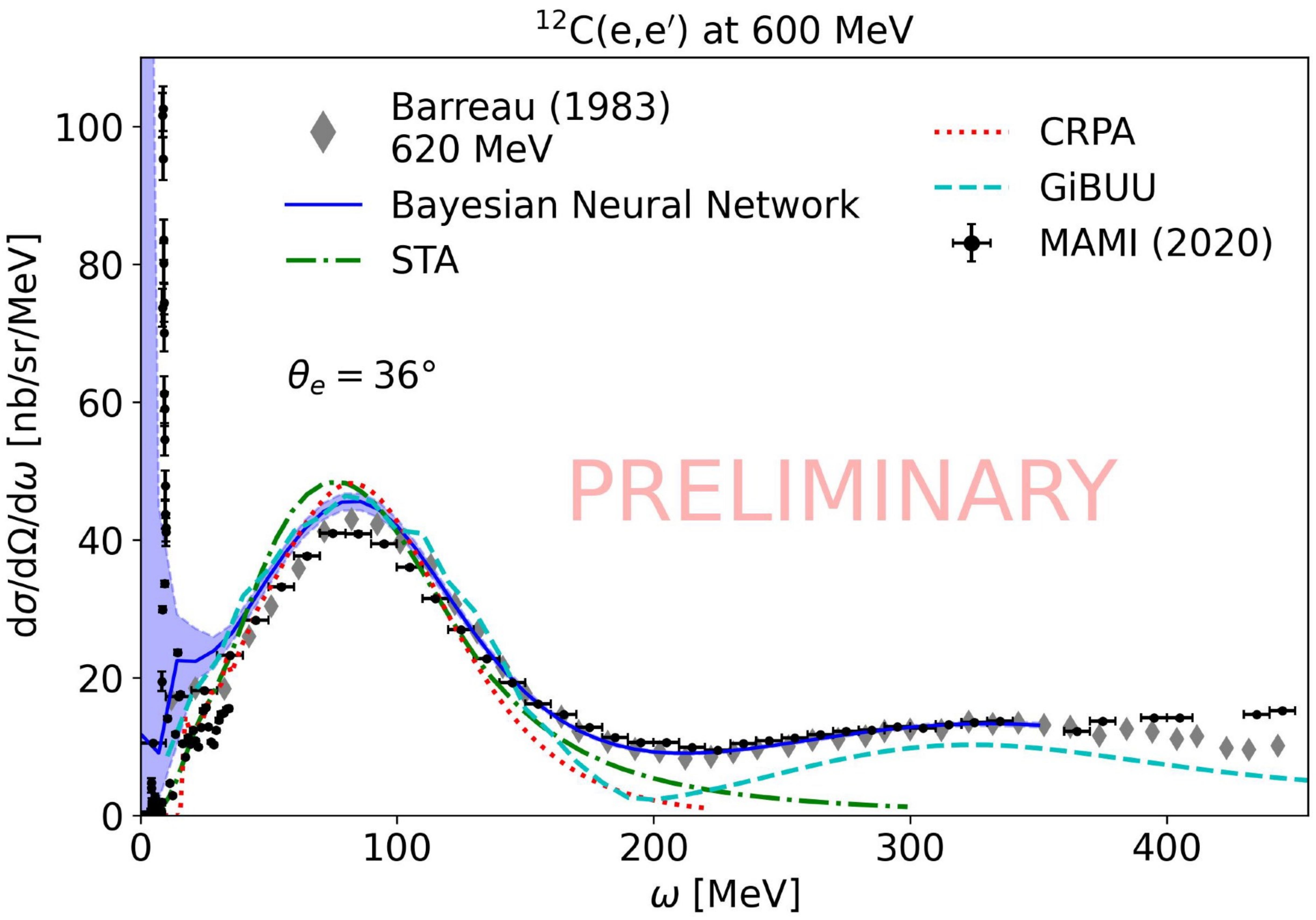
^{12}C inelastic electron scattering



^{12}C inelastic electron scattering

More kinematics…

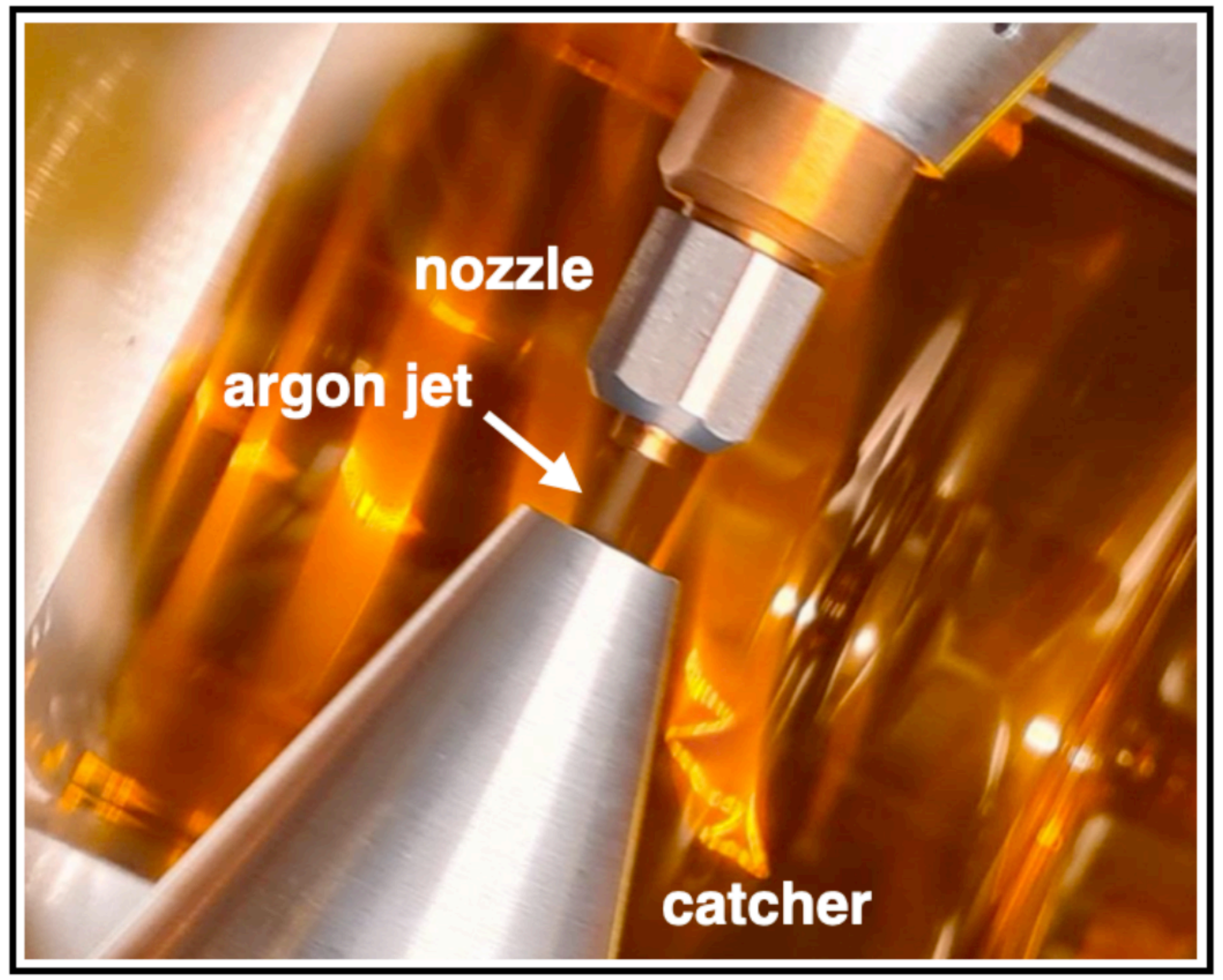


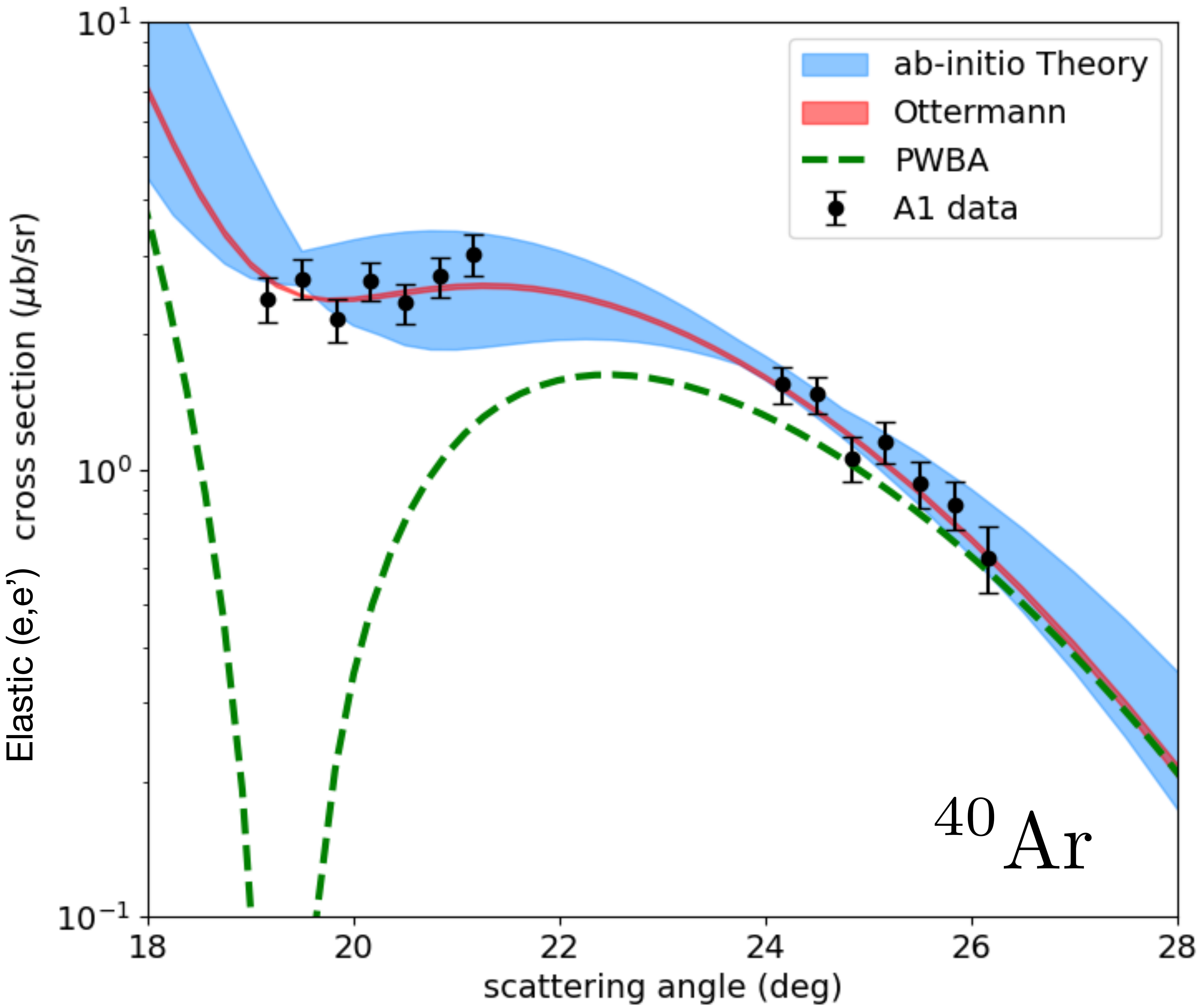


^{40}Ar elastic electron scattering

Littich, Doria et al., arXiv:2503.18965

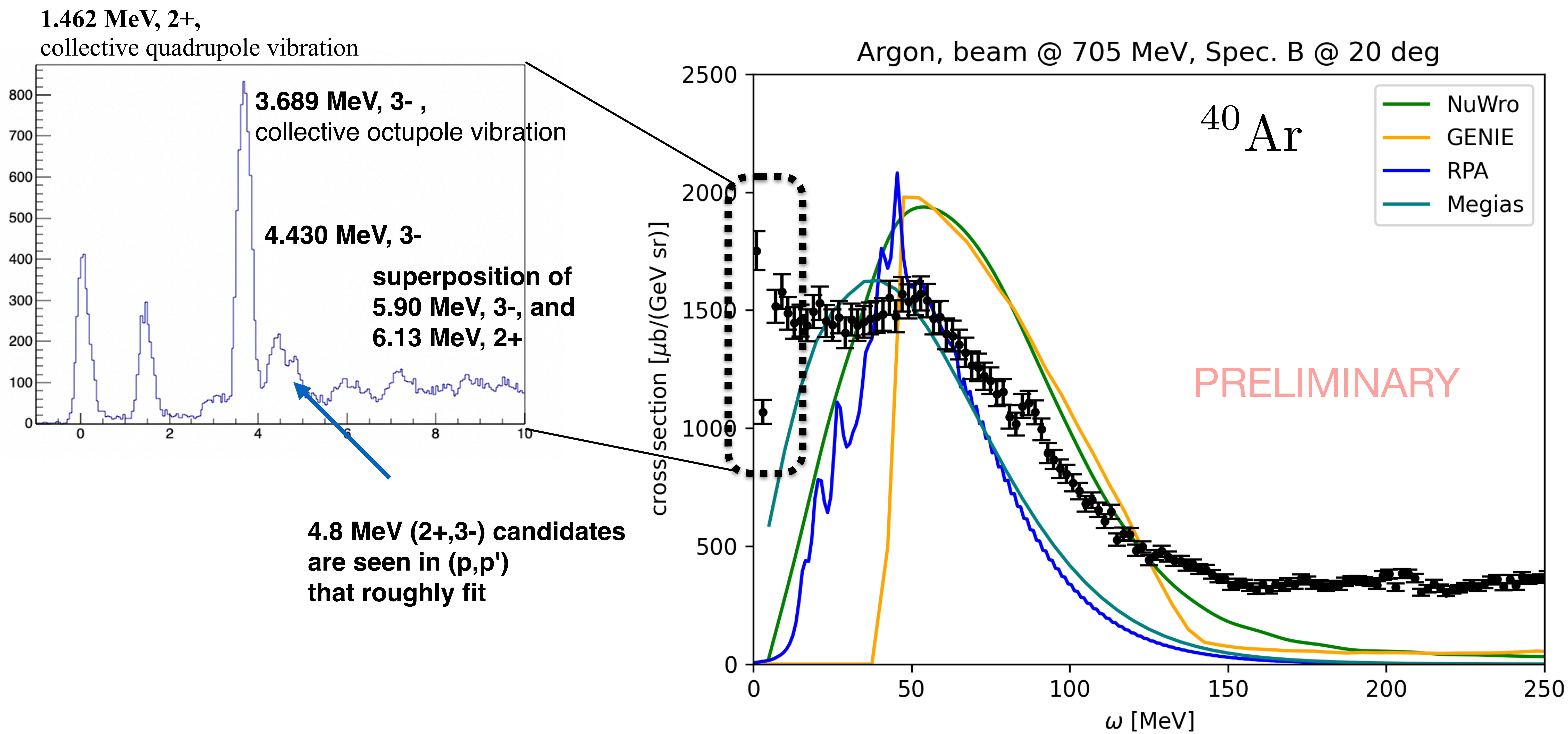
A1 with new gas-jet target





^{40}Ar inelastic electron scattering

Inelastic, in preparation



Total data on disk

Nucleus	Beam Energy (MeV)	Scattering angle (deg)	Target	Status
^{12}C	855	70	C-foil	Published
^{12}C	600	25	C-foil	Finalizing Analysis
^{12}C	600	28.8	C-foil	Finalizing Analysis
^{12}C	600	36	C-foil	Finalizing Analysis
^{12}C	600	60	C-foil	Finalizing Analysis
^{12}C	600	70	C-foil	Finalizing Analysis
^{40}Ar	705	20	Jet Target	Analysis in progress
^{40}Ar	705	32	Jet Target	Analysis in progress
^{16}O	600	30	Sapphire (Al_2O_3)	Analysis Started
^{16}O	600	70	Sapphire (Al_2O_3)	Analysis Started
^{44}Ti	600	30	Ti-foil	To analyze
^{44}Ti	600	70	Ti-foil	To analyze

Conclusions and outlook

- Remarkable progress in ab initio calculations
- Successful interplay of theory and experiment
- Electroweak processes are fascinating because they allow to connect nuclear physics to other areas of physics
- Challenges ahead of us:
  open-shell nuclei, exclusive cross sections, pion-production, consistent optical potentials, …

Supported by:

PRiSMA Cluster of Excellence

Hadrons CRC 1660 Nuclei

MARIE CURIE ACTIONS

Alexander von Humboldt Stiftung / Foundation

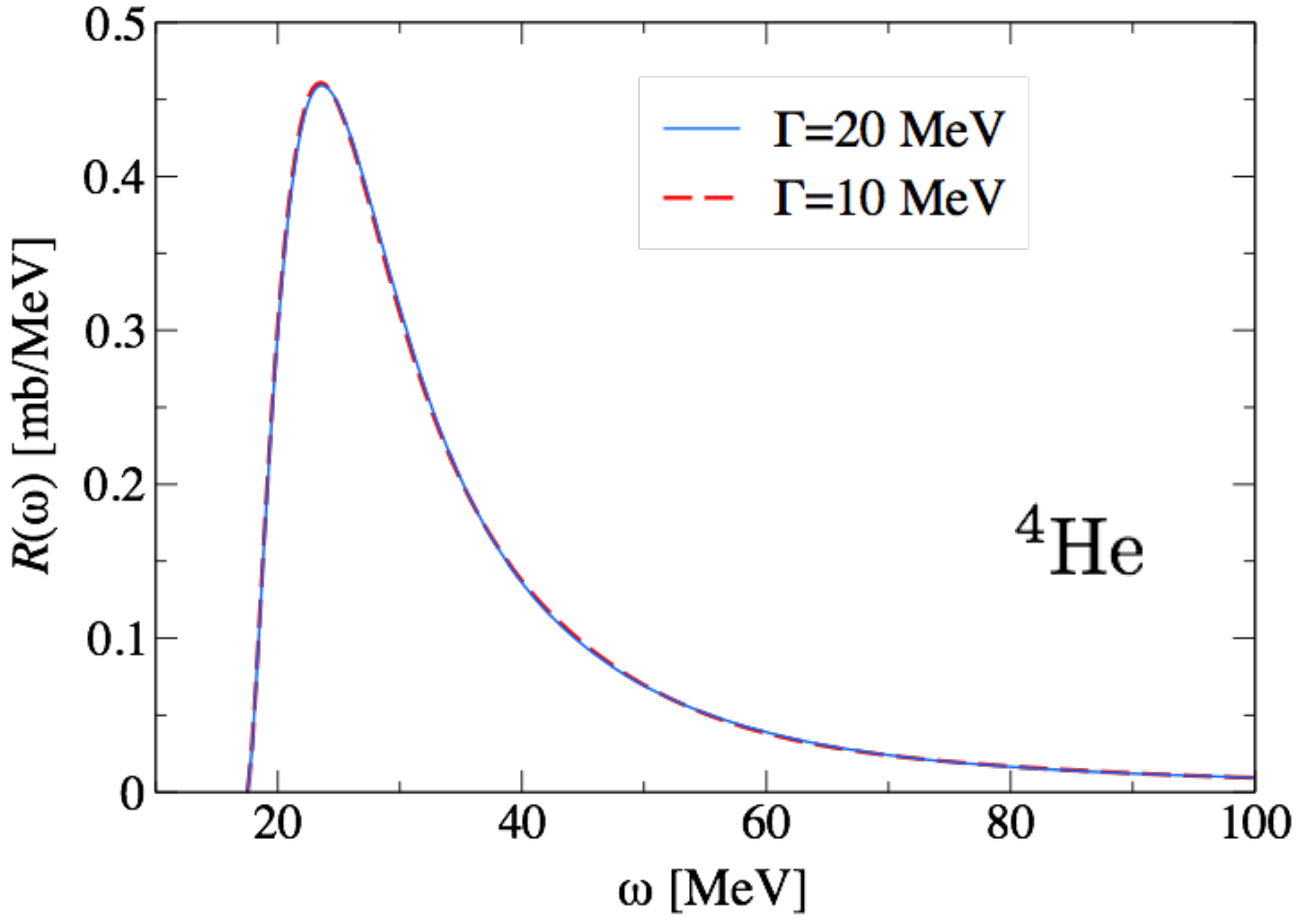
THANK YOU

The Lorentz integral transform (LIT)

The inversion is performed numerically with a regularization procedure (ill-posed problem)

Ansatz $$R(\omega) = \sum_{i}^{I_{\max}} c_i \chi_i(\omega, \alpha) \quad \Longrightarrow \quad L(\sigma, \Gamma) = \sum_{i}^{I_{\max}} c_i \mathcal{L}[\chi_i(\omega, \alpha)]$$

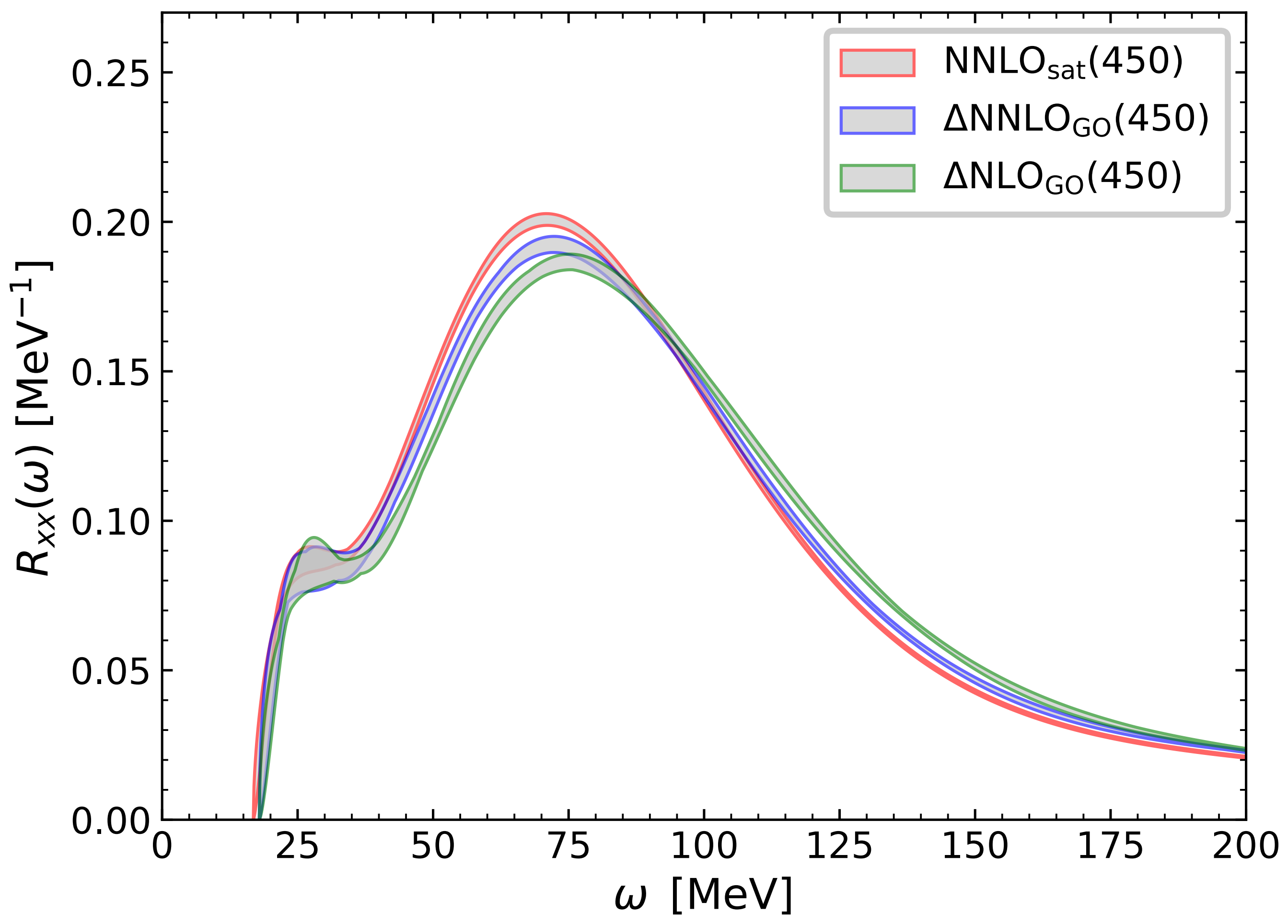
fit

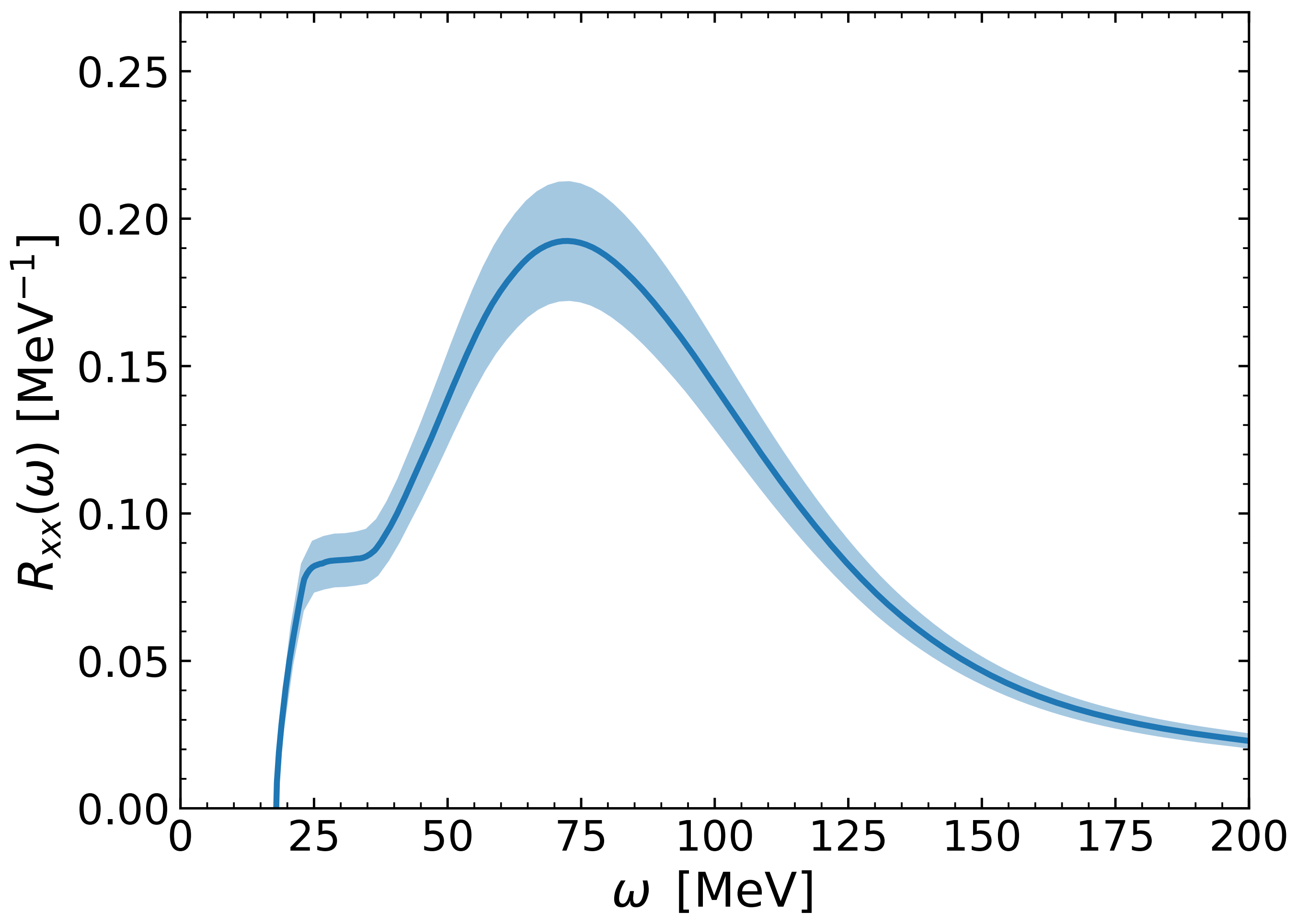


Message: Inversions are stable if the LIT is calculated precisely enough

Uncertainty estimation (responses)

Assessing EFT truncation error





Gaussian process (GP) to assess chiral truncation using 2 orders of expansion

Order k EFT prediction: $y_k(p) = y_{\mathrm{ref}}(p) \sum_{n=0}^{k} c_n(p) \left(\frac{p}{\Lambda}\right)^n$

EFT truncation error: $\delta y_k(p) = y_{\mathrm{ref}}(p) \sum_{n=k+1}^{\infty} c_n(p) \left(\frac{p}{\Lambda}\right)^n$

Draws from an underlying GP