Electron- and neutrino-nucleus scattering from first principles

Sonia Bacca

Many-body systems

Few-body systems

Lepton-nucleus scattering

ν-A scattering

$$\left.\frac{d^2\sigma}{d\Omega d\omega}\right|_{\nu/\bar{\nu}} = \sigma_0 \left[\ell_{00}R_{00} + \ell_{zz}R_{zz} + \ell_{0z}R_{0z} + \ell_{xx}R_{xx} \mp \ell_{xy}R_{xy}\right]$$

e-A scattering

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

Long baseline neutrino program

What do we need to do in ab-initio nuclear theory?

Target nuclei are ^{12}C, ^{16}O, and ^{40}Ar so we need to:

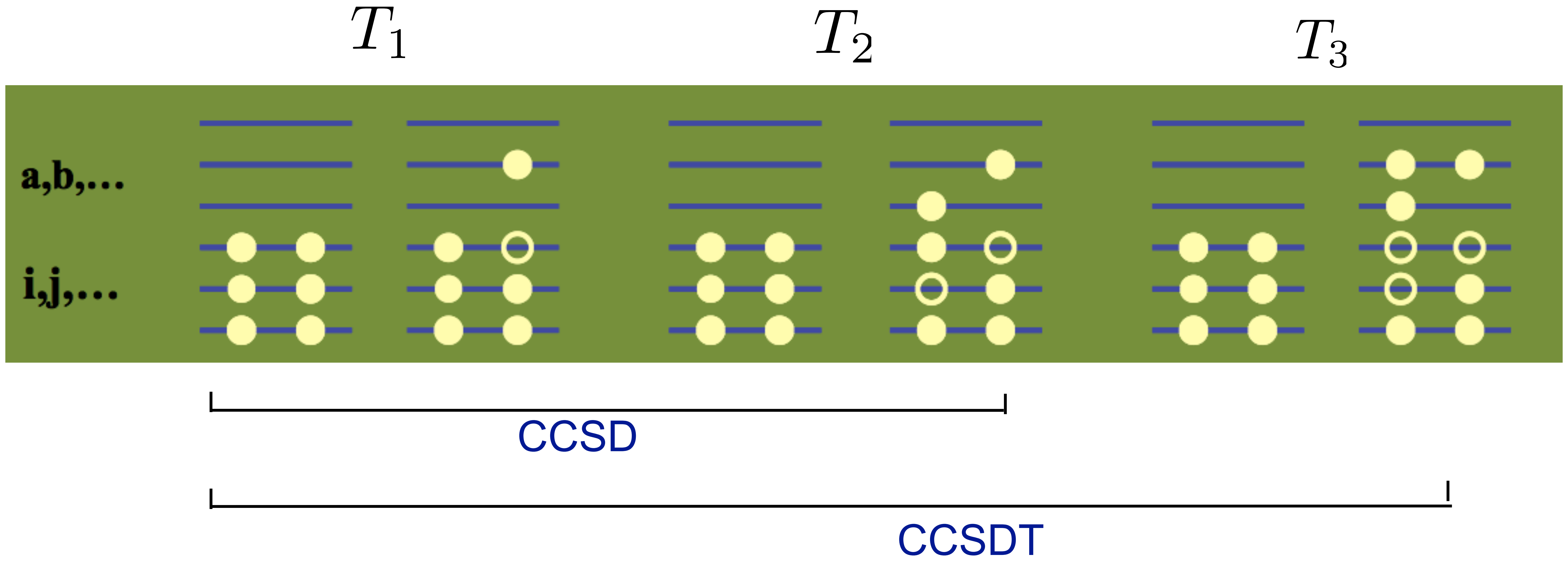
1. Solve the ground state
2. Calculate response functions

1) Solve 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

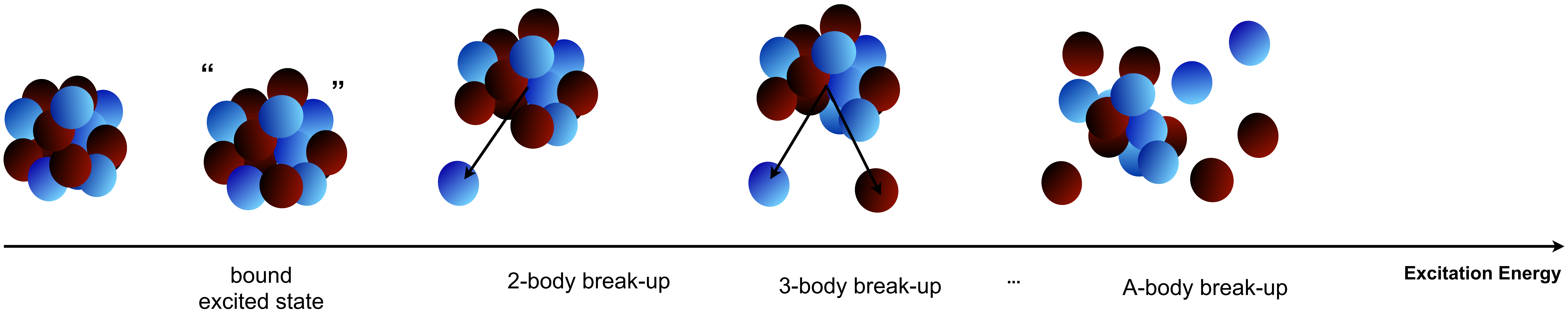


2) Calculate response functions

$$R(\omega) = \sum_f \left| \left\langle \psi_f \left| \Theta \right| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$$

Depending on E_f, many channels may be involved

Exact knowledge limited

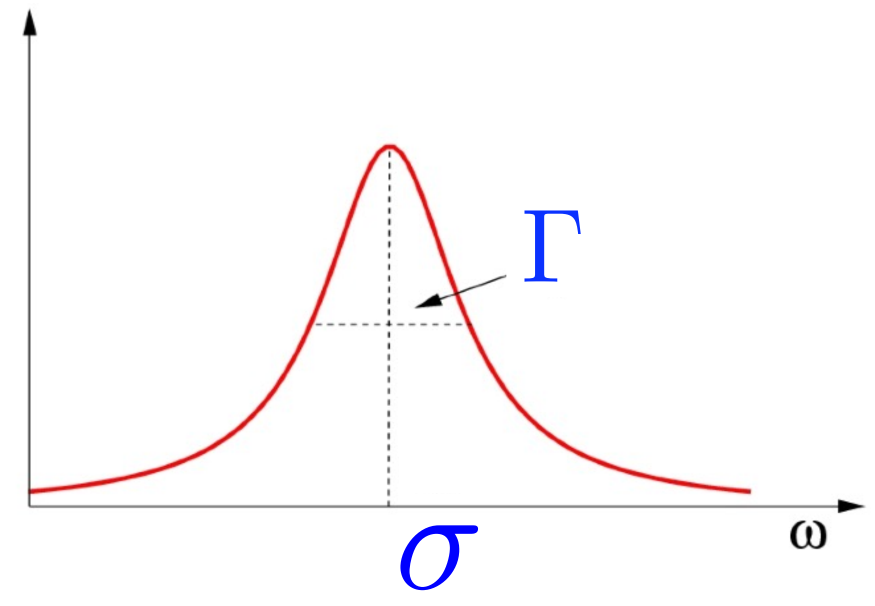


2) Calculate response functions

Lorentz Integral Transform

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

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



Reduce to a bound-state-like equation

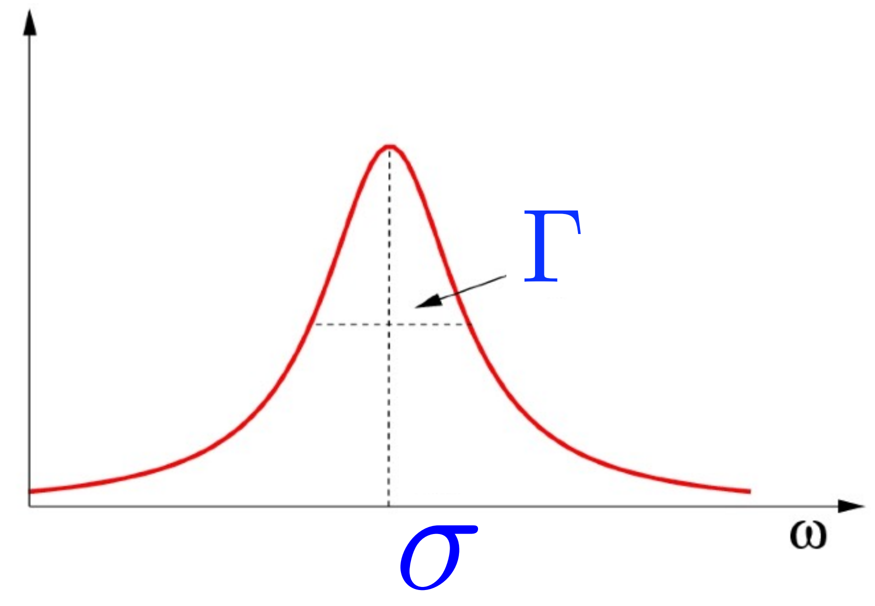
$$(H - E_0 - \sigma + i\Gamma)\,|\,\tilde{\psi}\rangle = \Theta\,|\,\psi_0\rangle$$

2) Calculate response functions

Lorentz Integral Transform

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

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



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

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

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

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

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

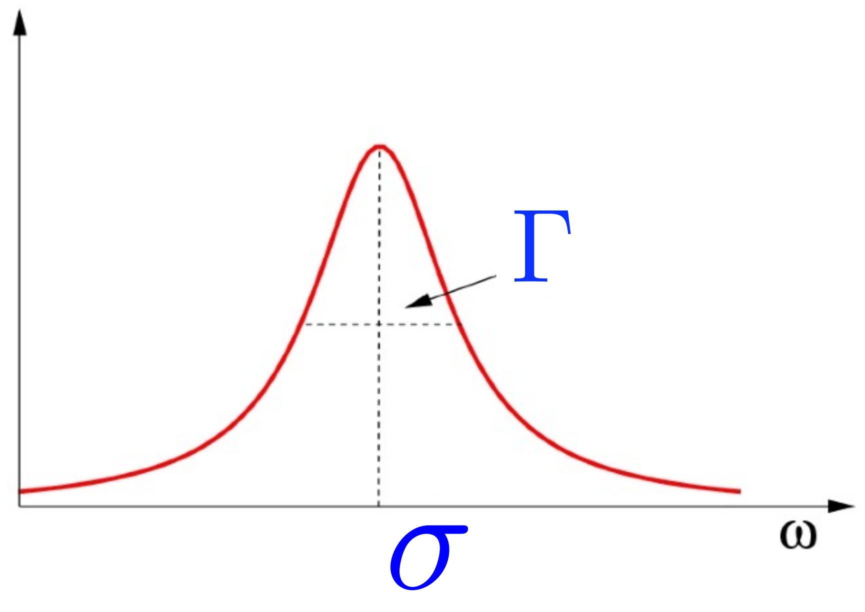
2) Calculate response functions

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

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

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

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

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

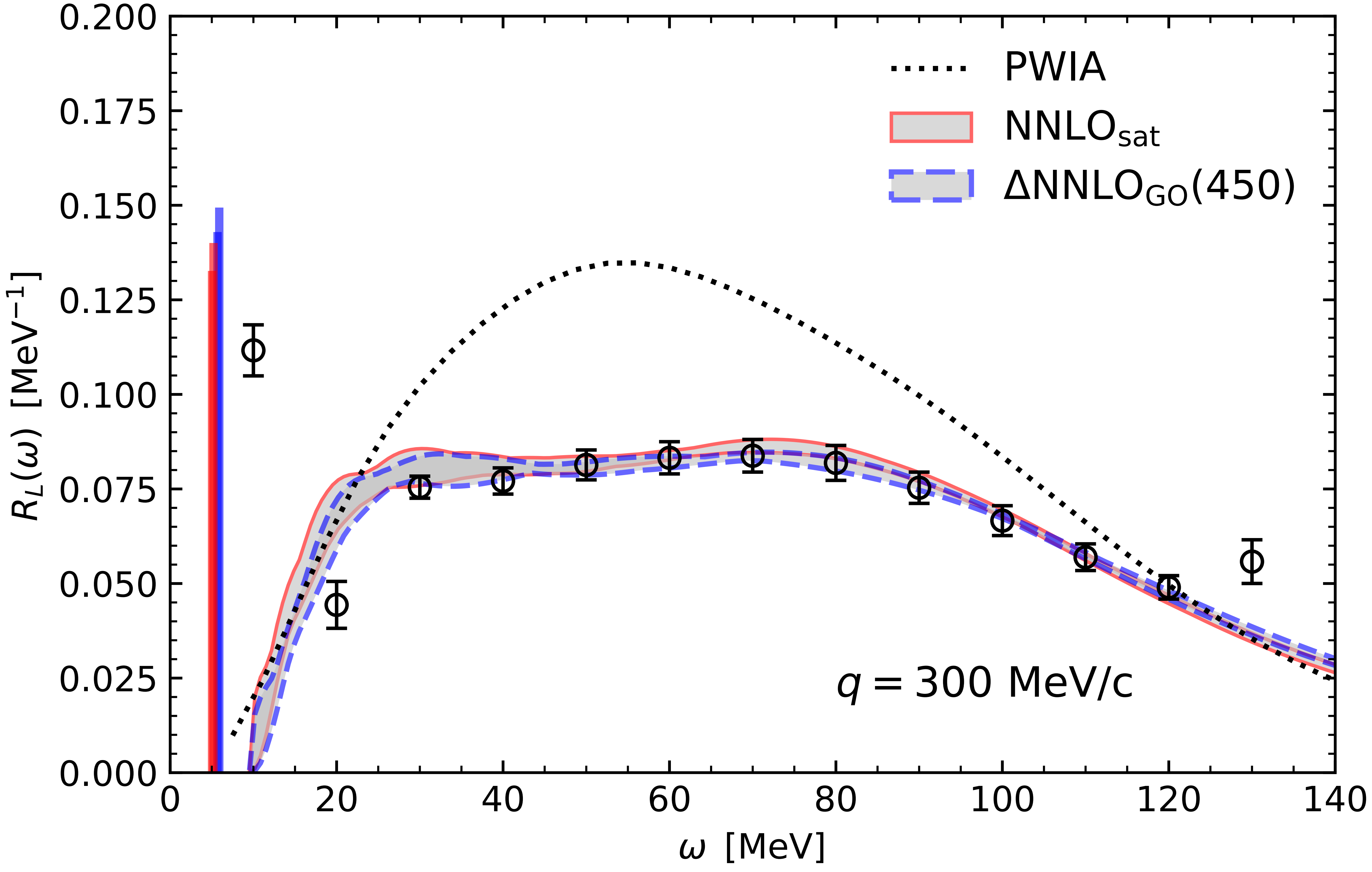
Applications to lepton-nucleus scattering

with LIT-CC

Electron scattering

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

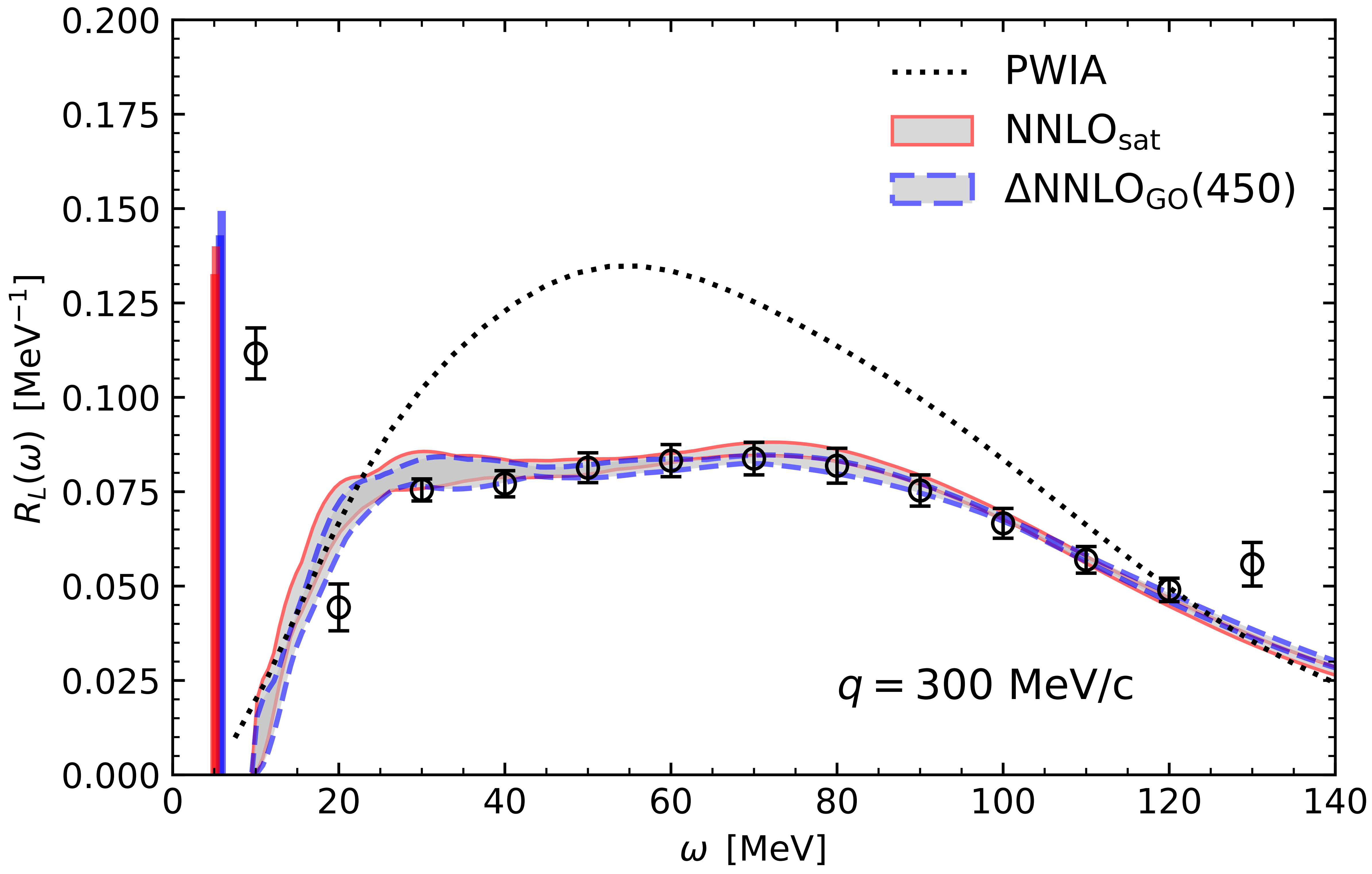
Sobcyzk, Acharya, SB, Hagen, PRL 127 (2021) 7, 072501



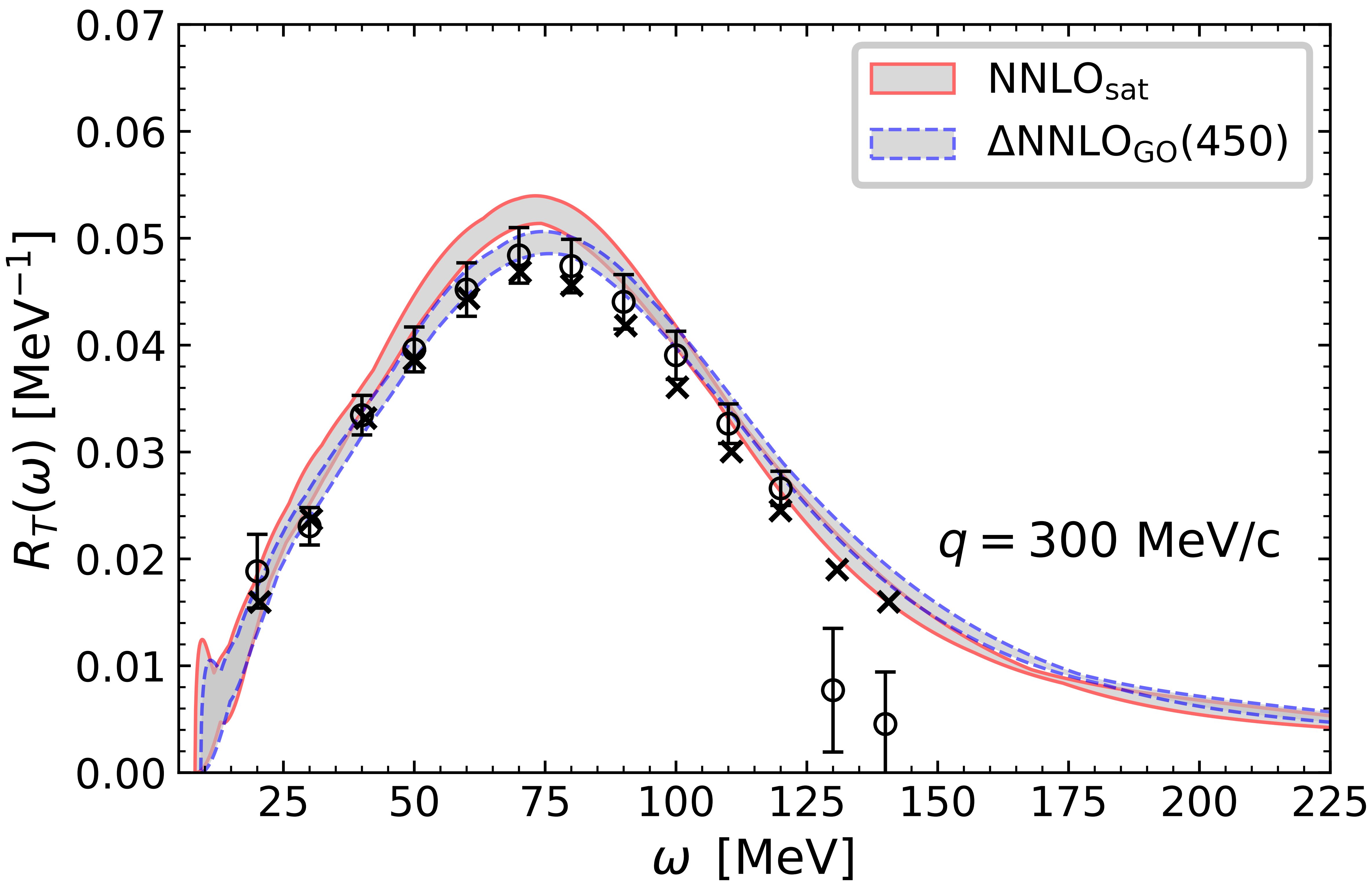
Electron scattering

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

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



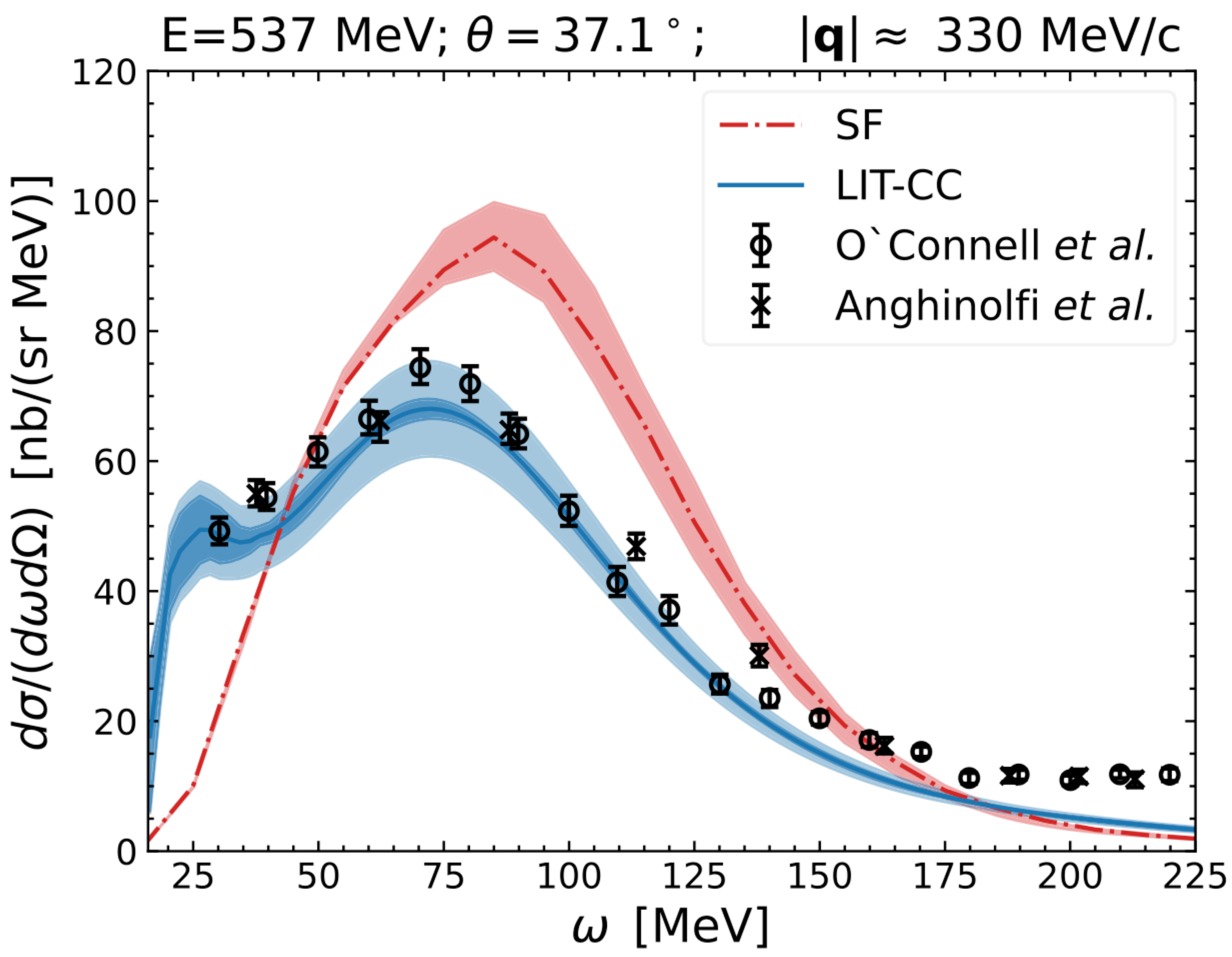
Sobczyk, Acharya, SB, G. Hagen, PRC 109 (2024) 2, 025502



Electron scattering

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

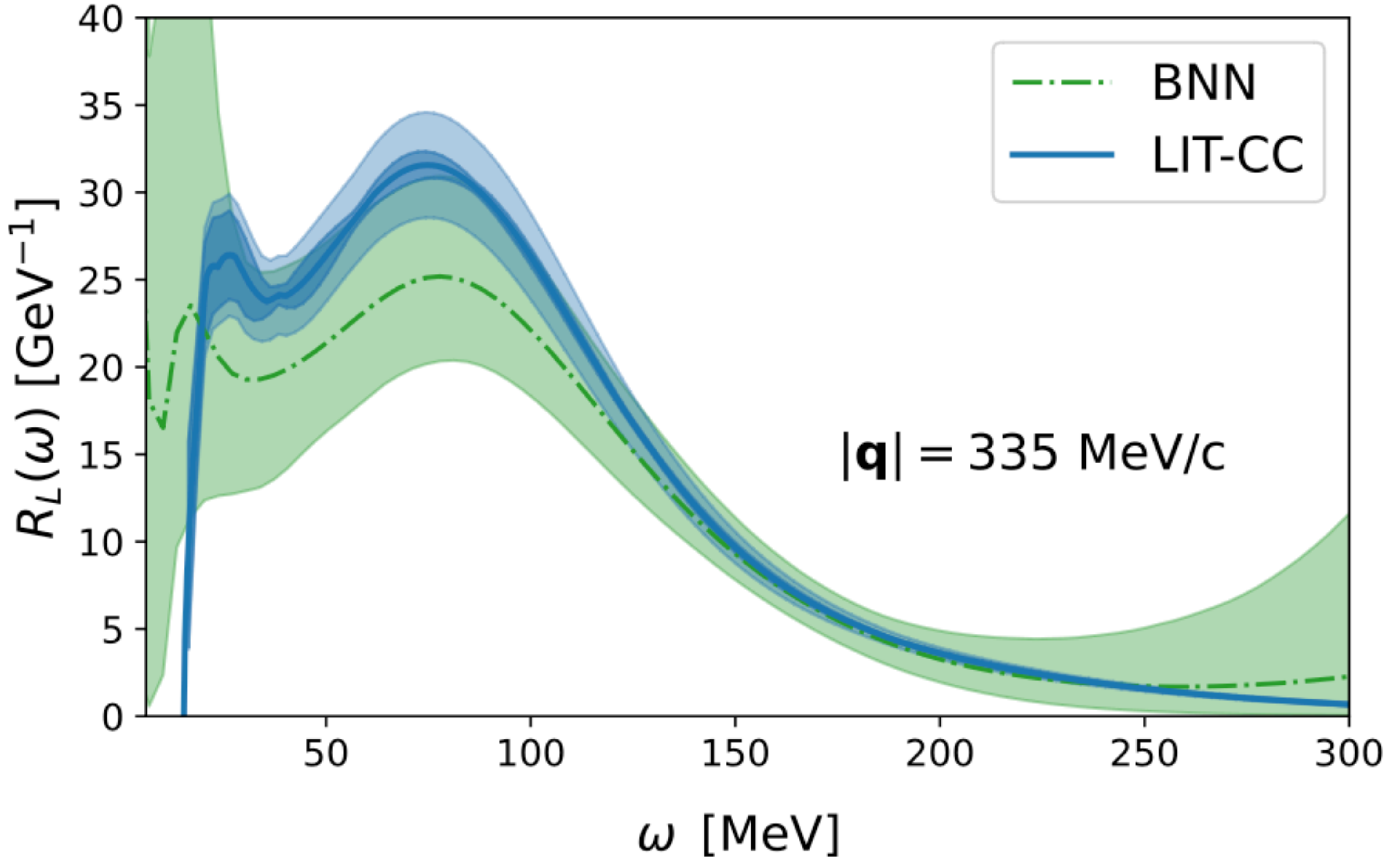
Acharya, Sobczyk, SB, et al., Phys. Rev. Lett. 134, 202501 (2025)

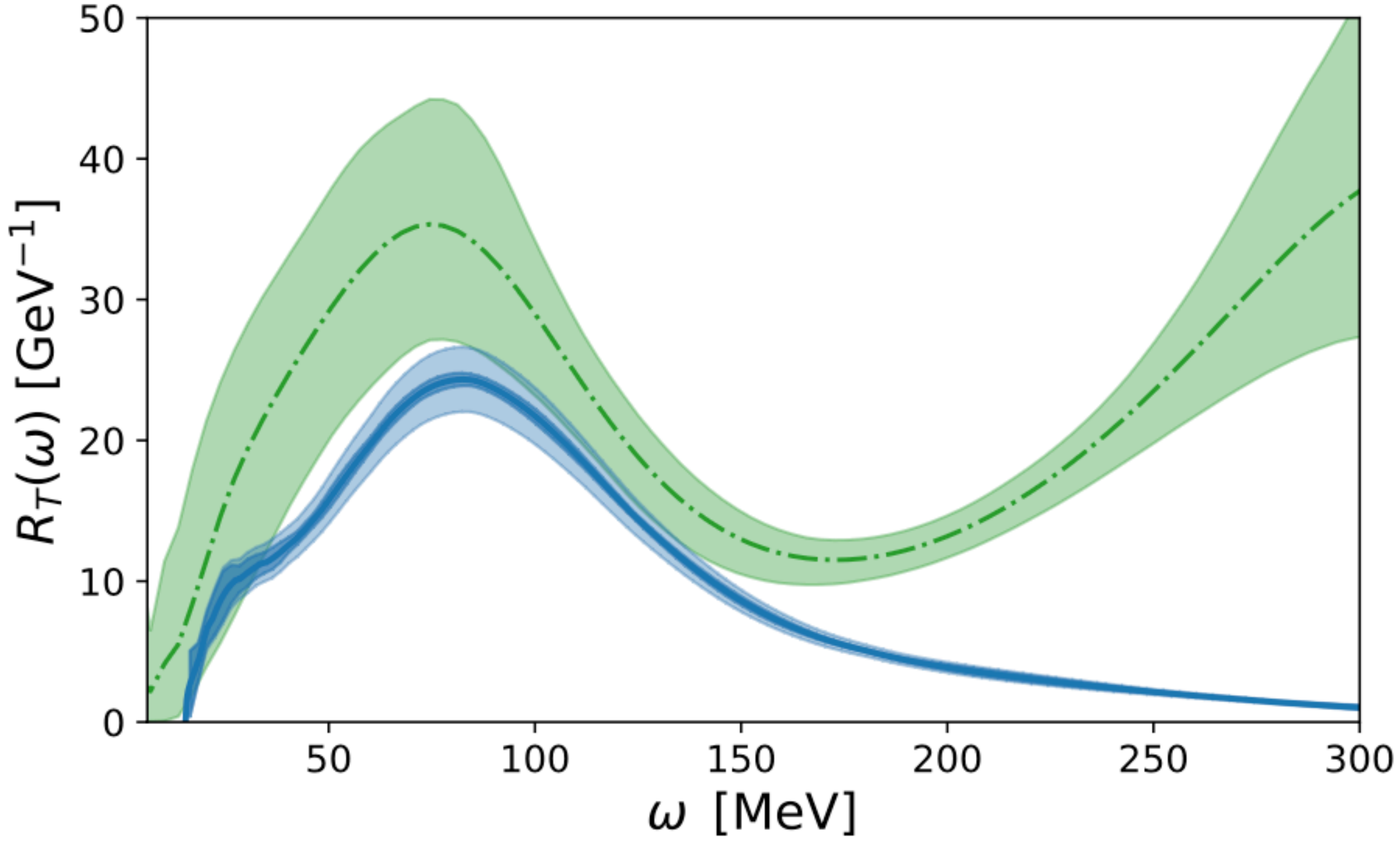


Electron scattering

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

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



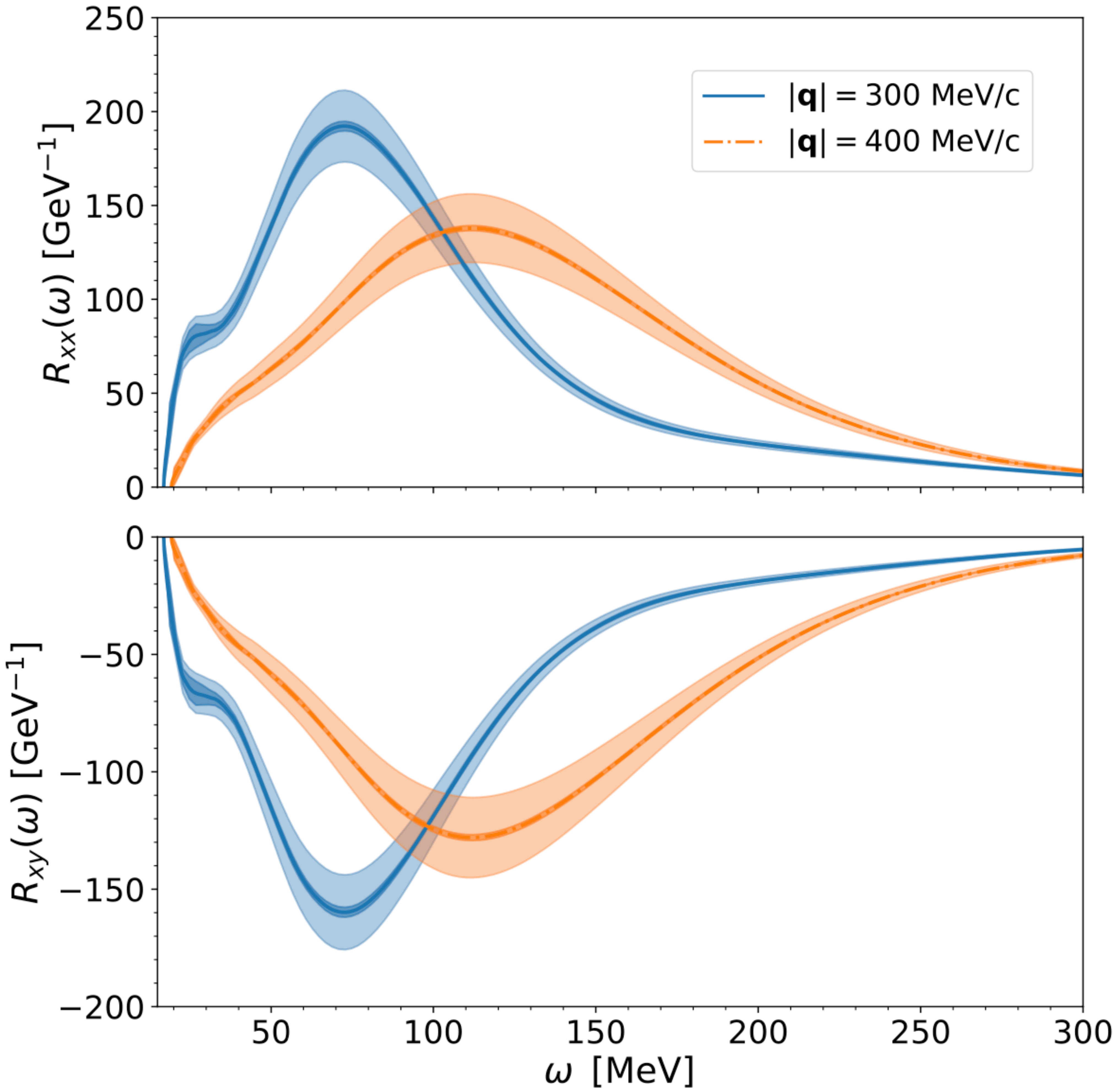


BNN from Sobczyk et al., arXiv:2406.06292

Towards neutrino-nucleus scattering

^{16}O weak responses

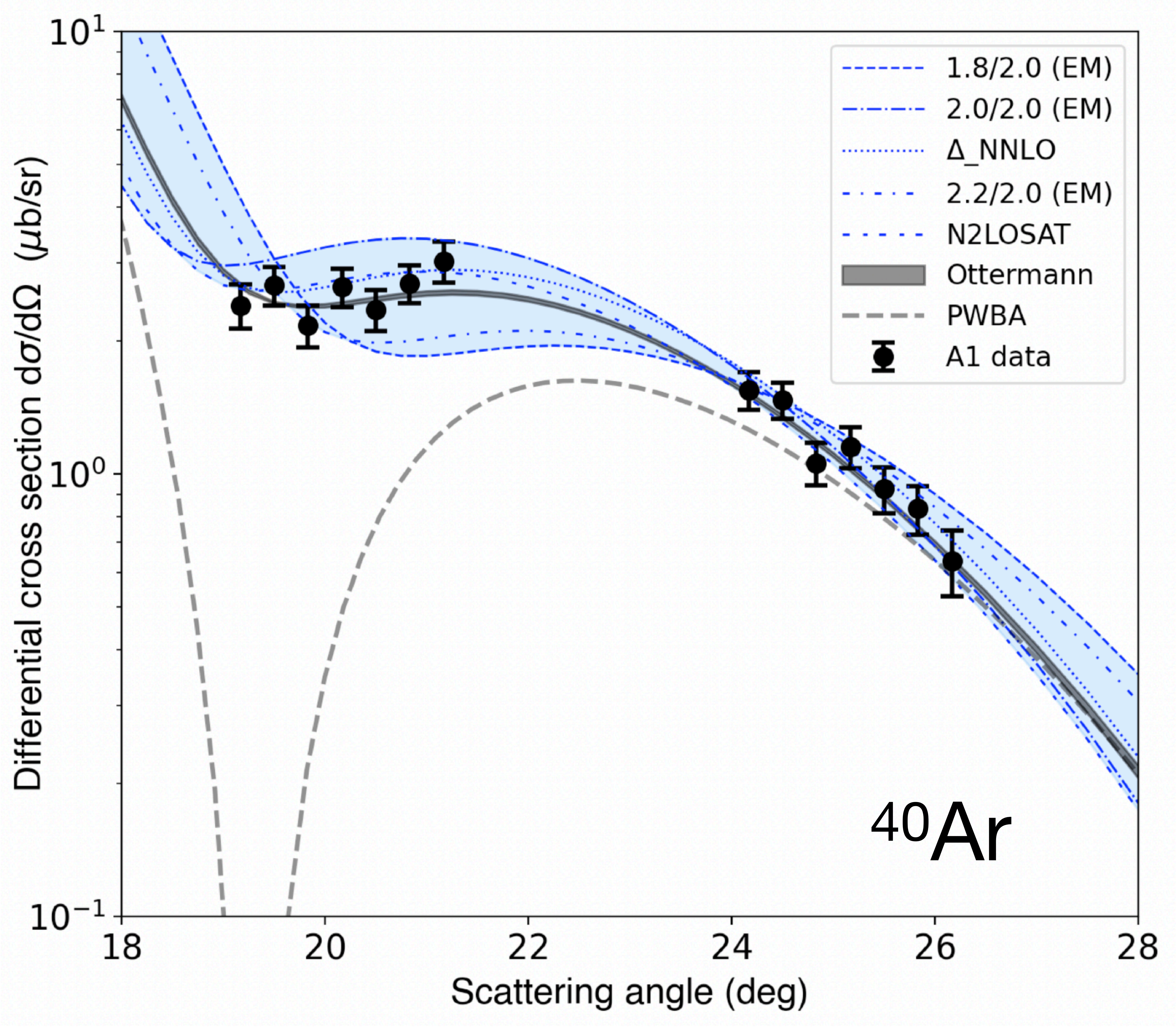
Acharya, Sobczyk, SB, et al., Phys. Rev. Lett. 134, 202501 (2025)



Challenges

How to tackle ^{40}Ar?

Littich et al., Eur.Phys.J.A 61 (2025)



Challenges

How to tackle ^{40}Ar?

- Fractional filling coupled-cluster theory

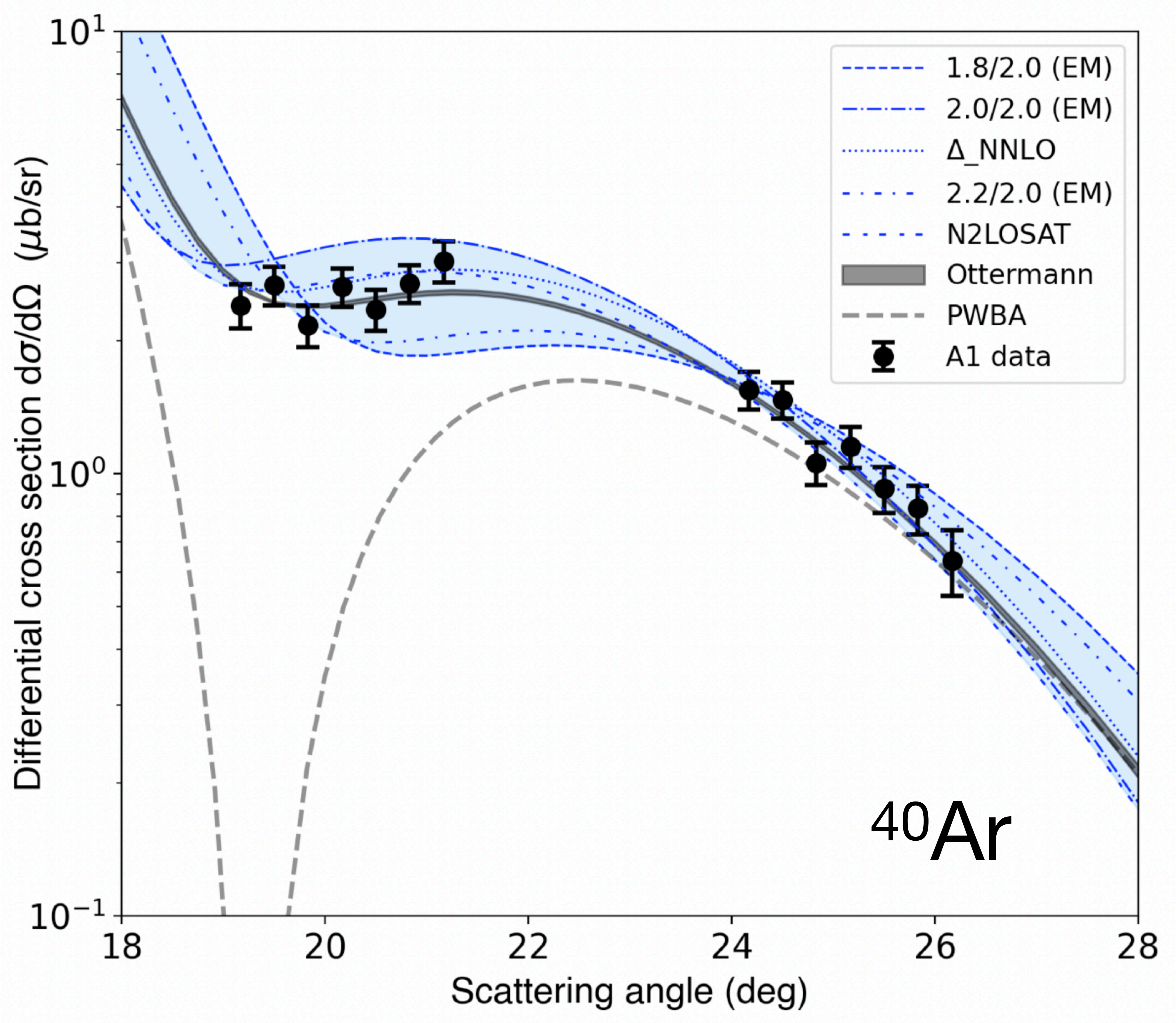
  Cohen et al., Phys. Rev. B **77**, 115123 (2008)

- Deformed coupled-cluster

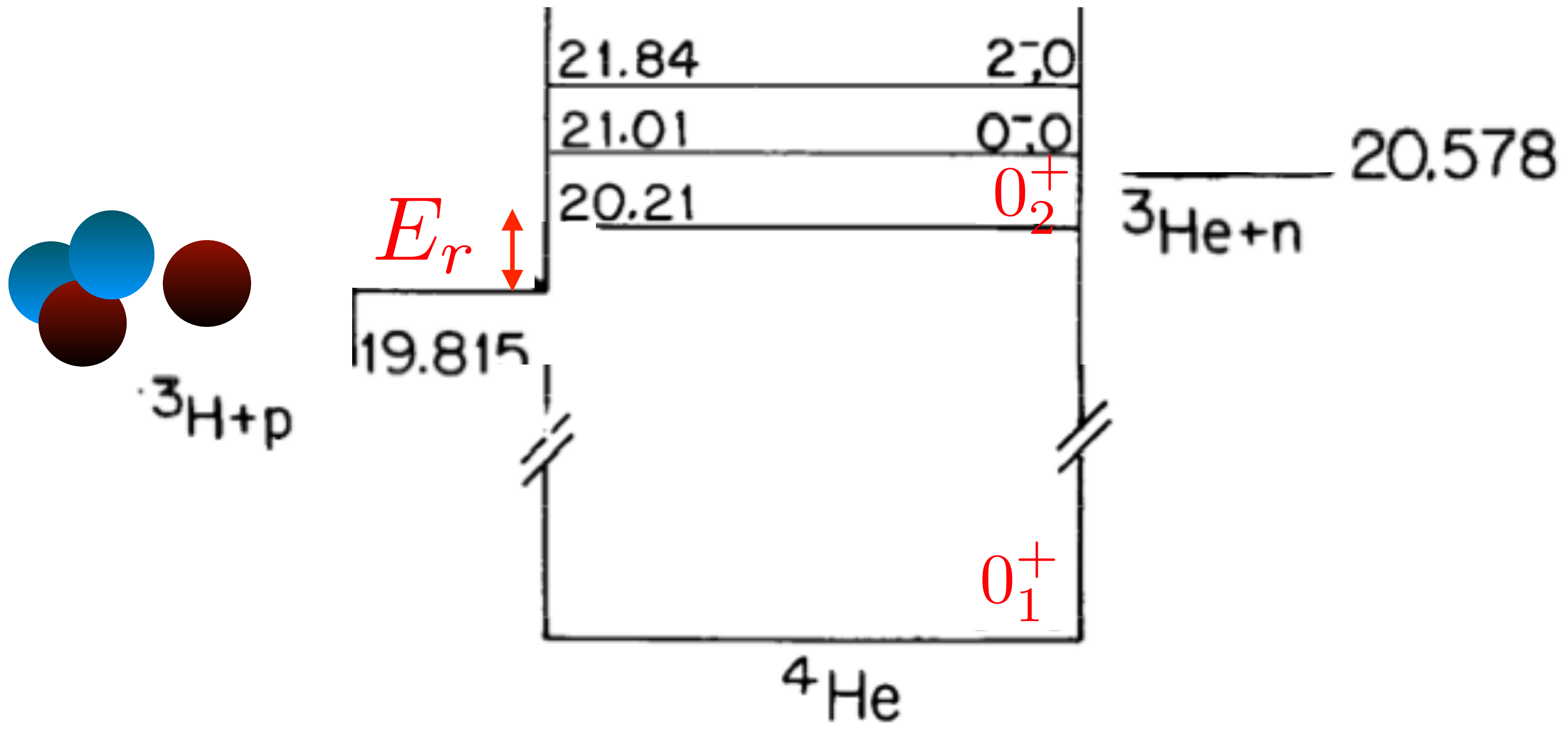
  Sun et al., Phys. Rev. C **108**, 014307 (2023)

- Any other ideas?

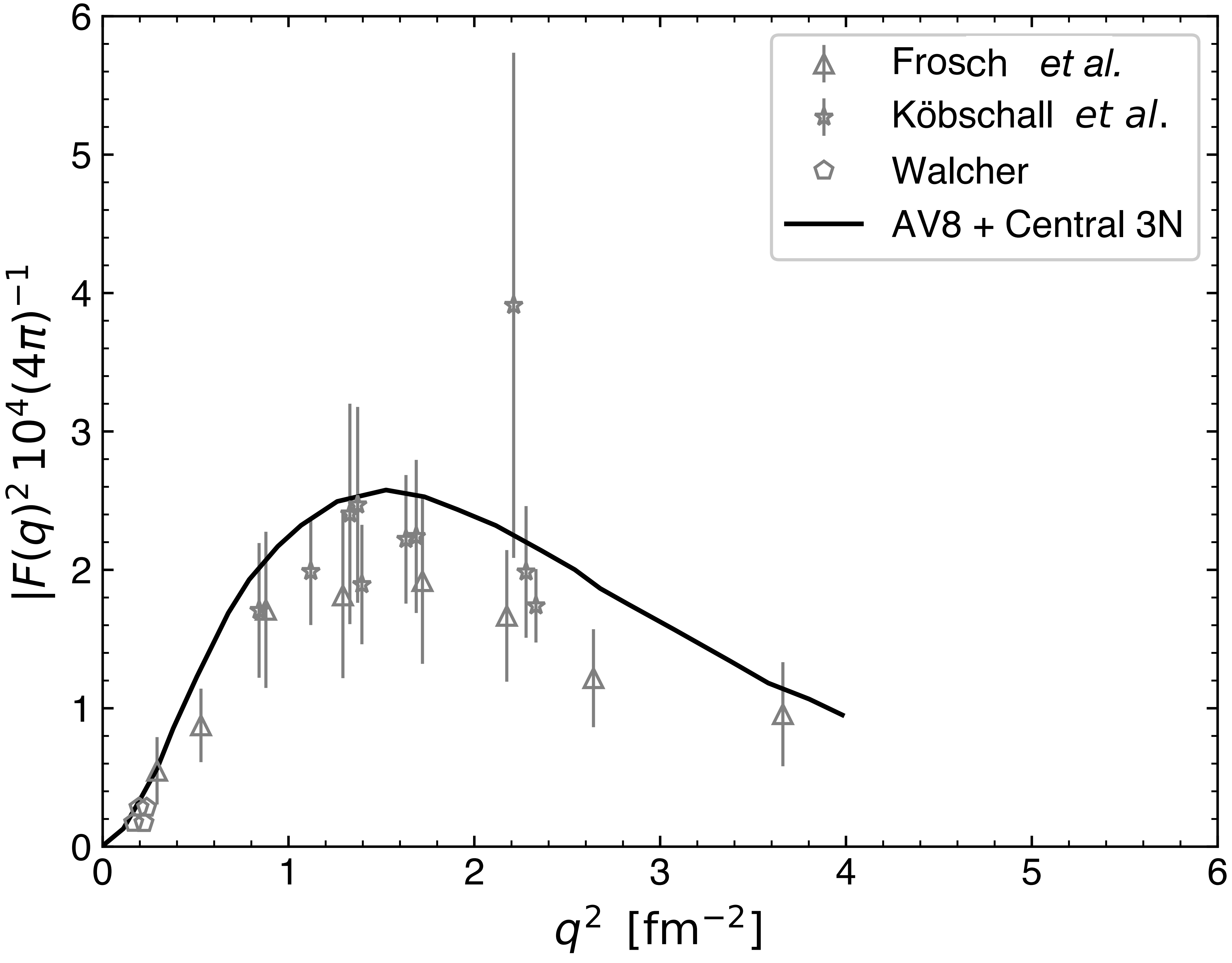
Littich et al., Eur.Phys.J.A 61 (2025)



Few-body system: the α-particle



Hiyama et al. PRC **70**, 031001(R) (2004)



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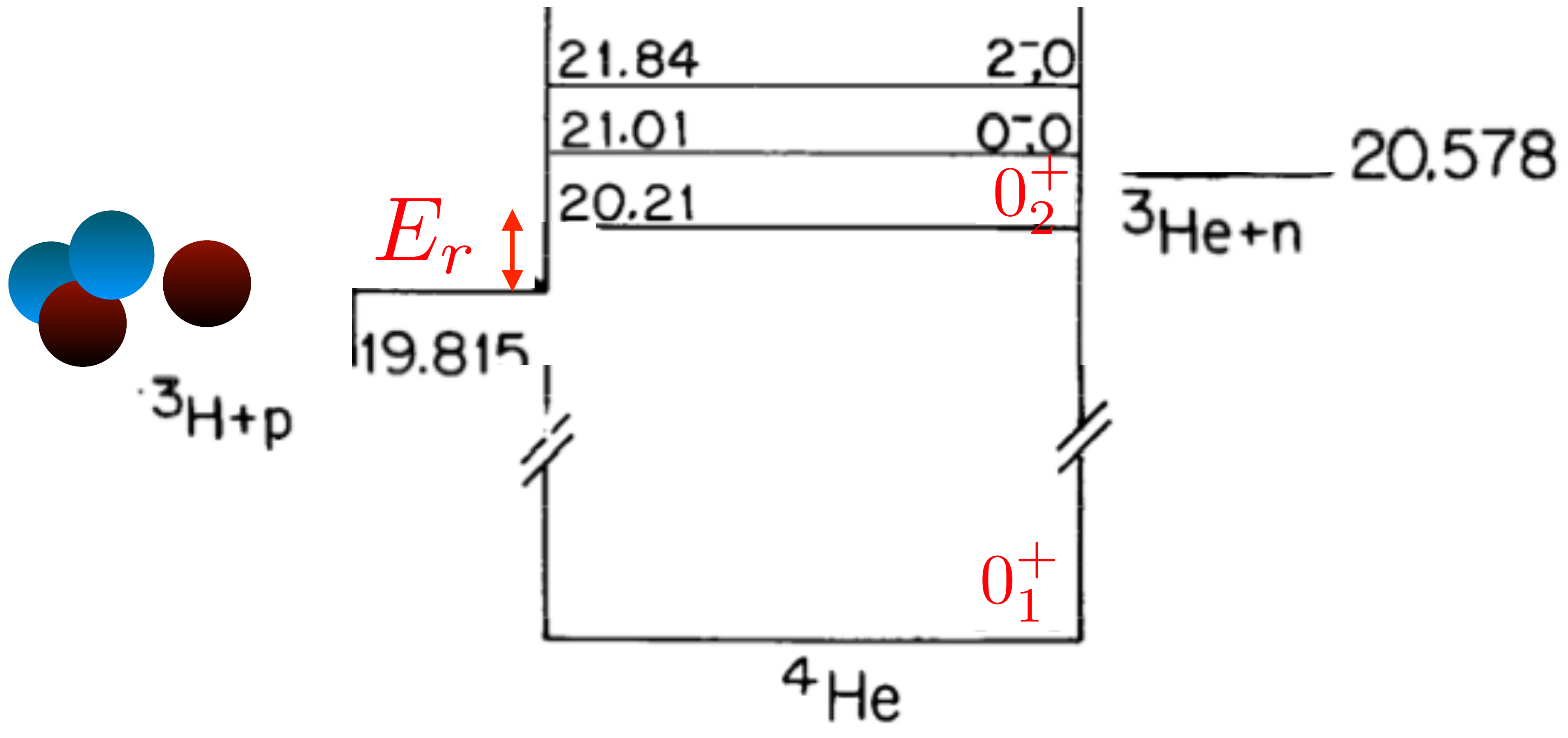
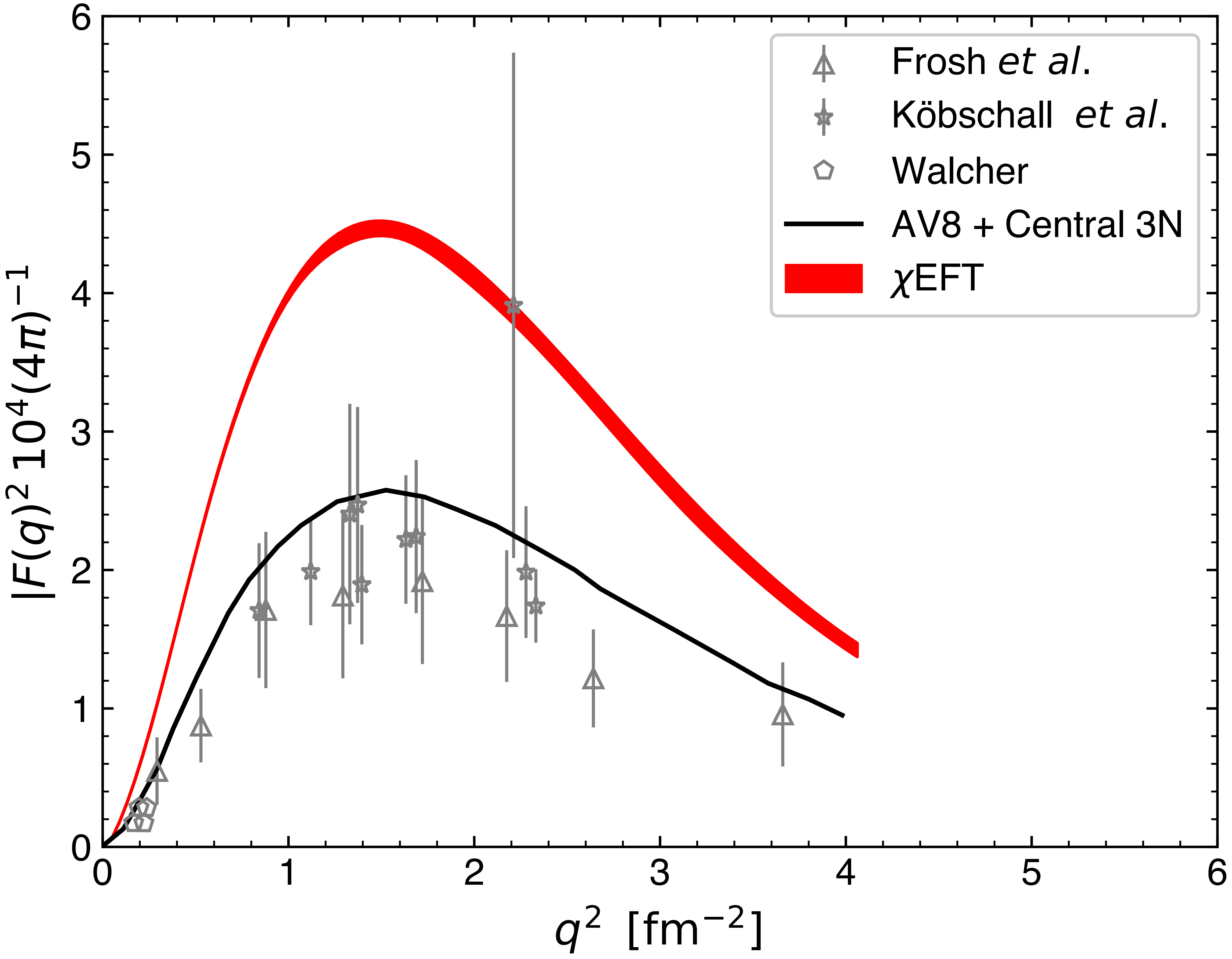
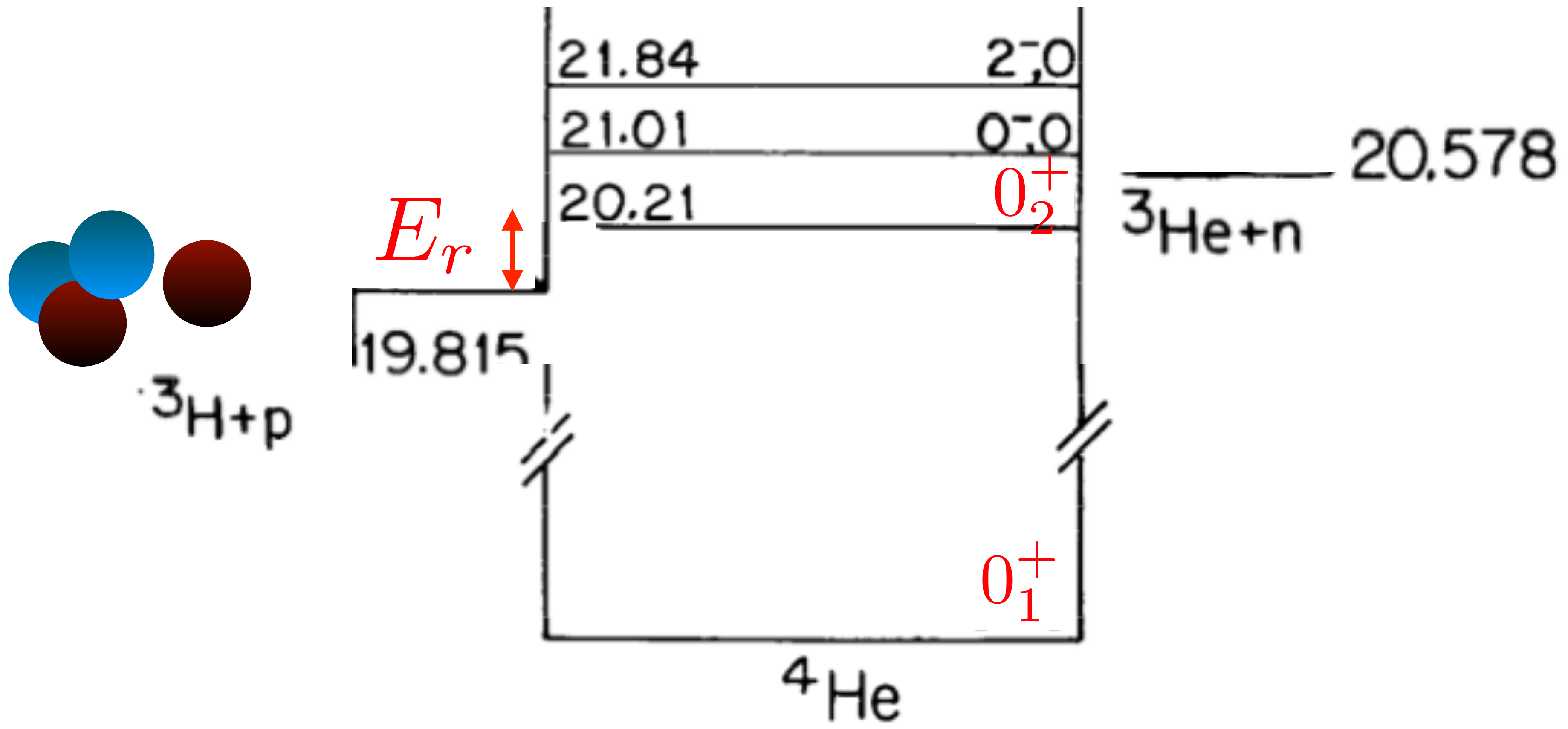


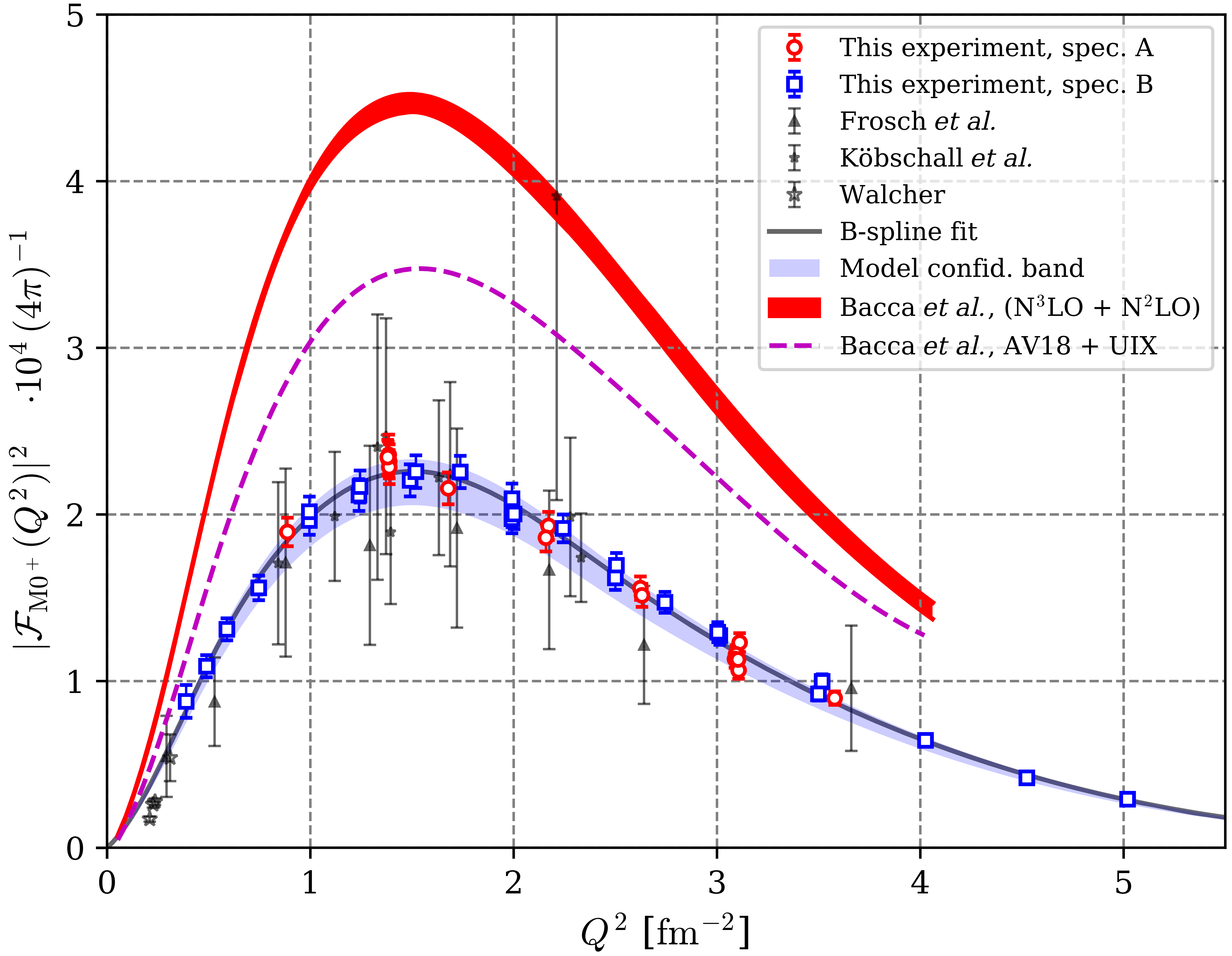
SB et al. PRL **110**, 042503 (2013)



Few-body system: the α-particle

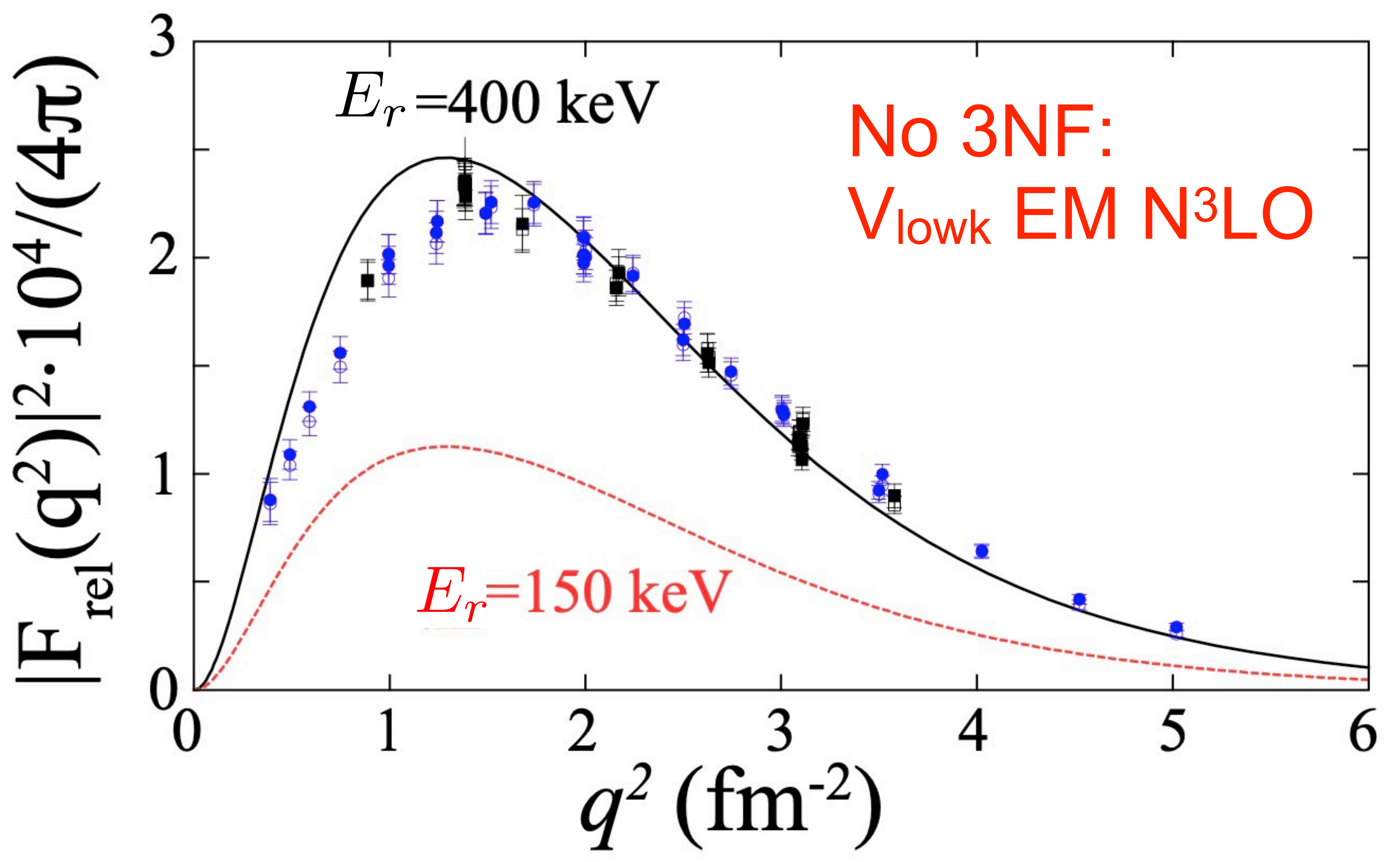


Kegel et al. PRL **130**, 152502 (2023)



Recent calculations

Michel, Nazarewicz, Ploszajczak et al., PRL 131, 242502 (2023)
Method: NCGSM-CC



Tune E_r to fit Kegel data ⇒ E_r=0.4 Mev

Erratum Phys. Rev. Lett. 133, 239901 (2024)

Tune E_r to fit Kegel data ⇒ E_r=0.12 Mev

Recent calculations

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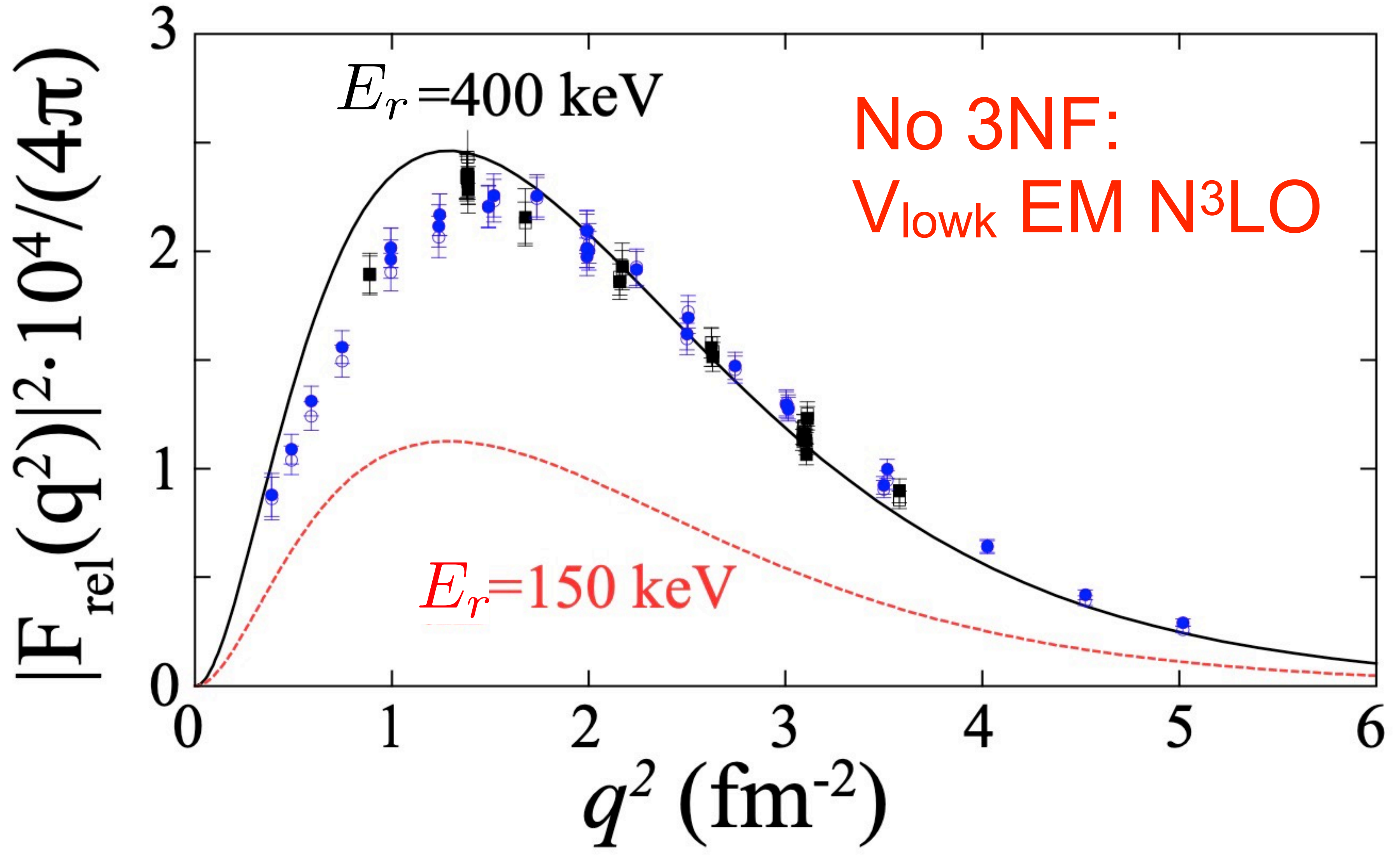
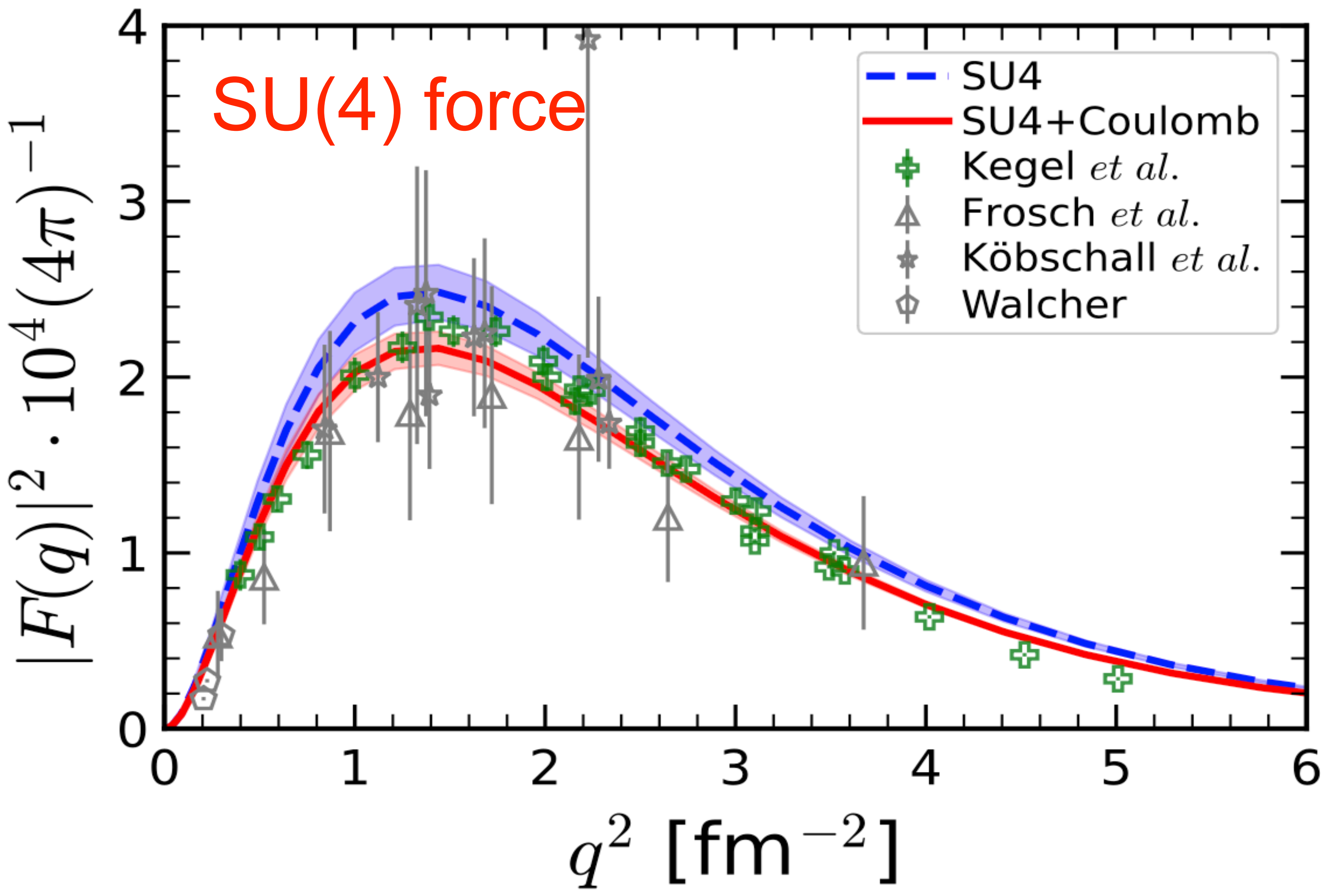
Method: NCGSM-CC



Meißner, Shen, Elhatisari, Lee, PRL 132, 062501 (2024)
Method: LatticeEFT



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Erratum Phys. Rev. Lett. 133, 239901 (2024)

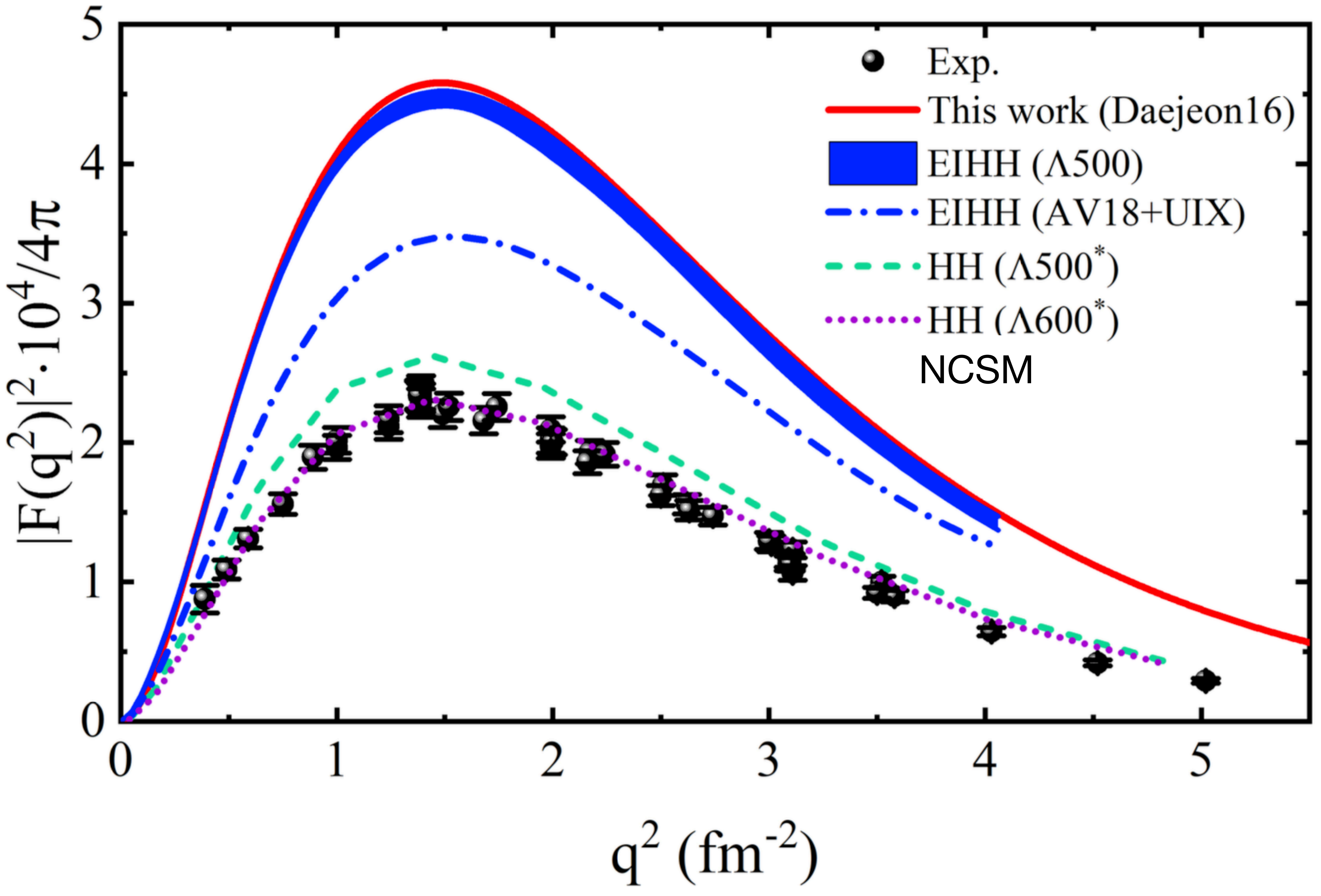
Tune E_r to fit Kegel data ⇒ E_r=0.12 Mev

E_r =0.40(9) MeV (not fit to data)

Most recent calculations

HH from Viviani et al, FBS (2024)

NCSM from P. Yin et al, 2412.18037



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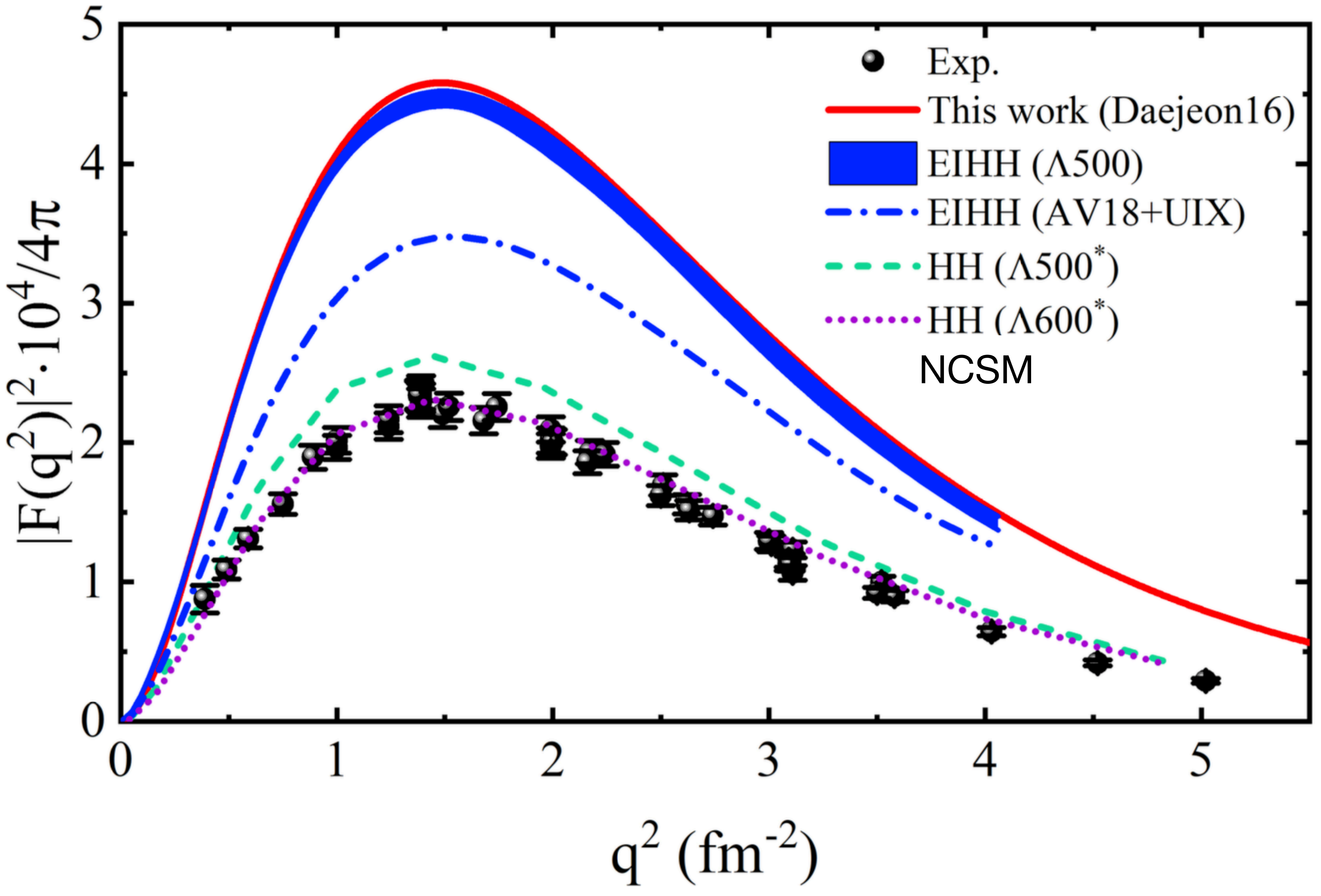
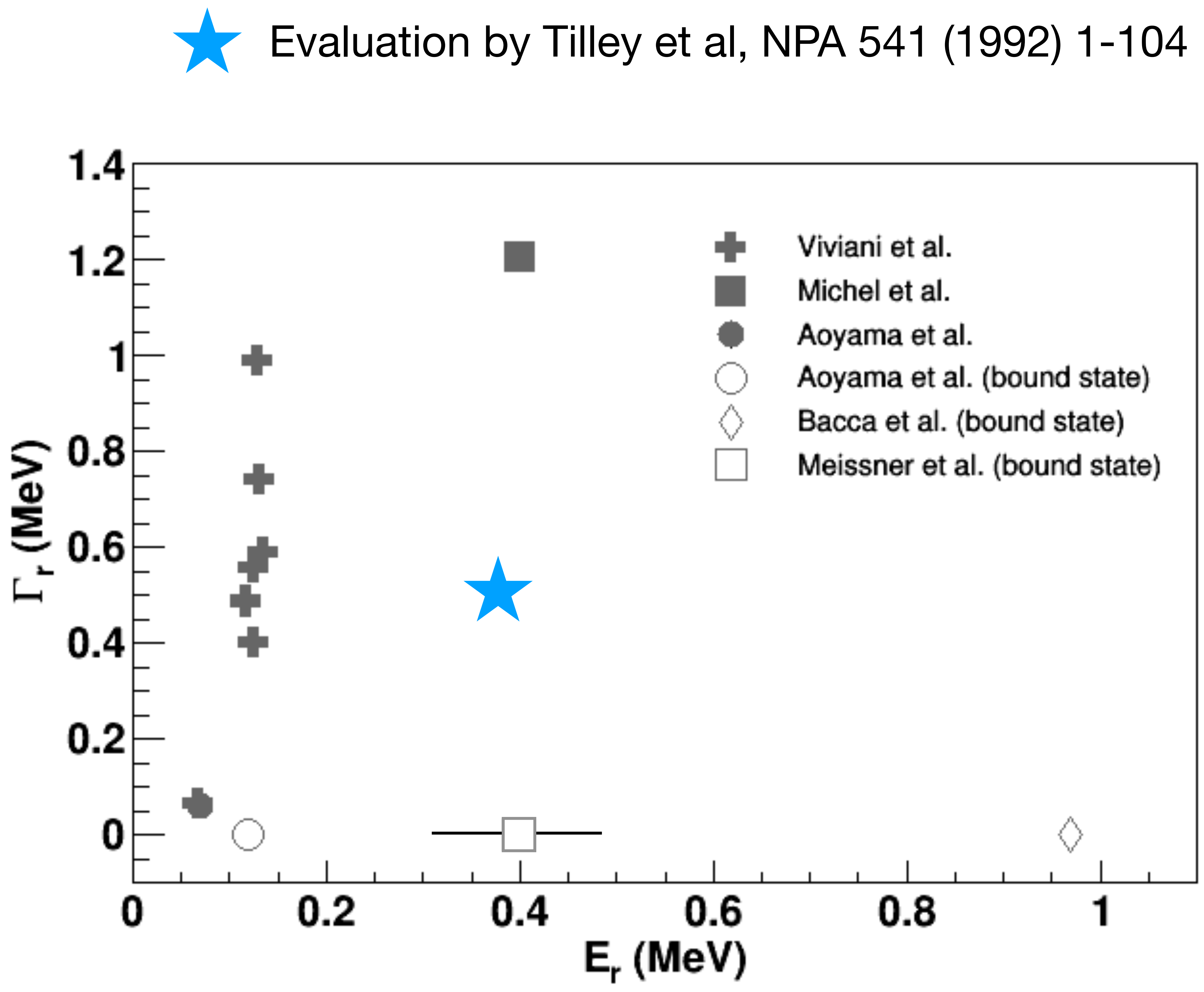


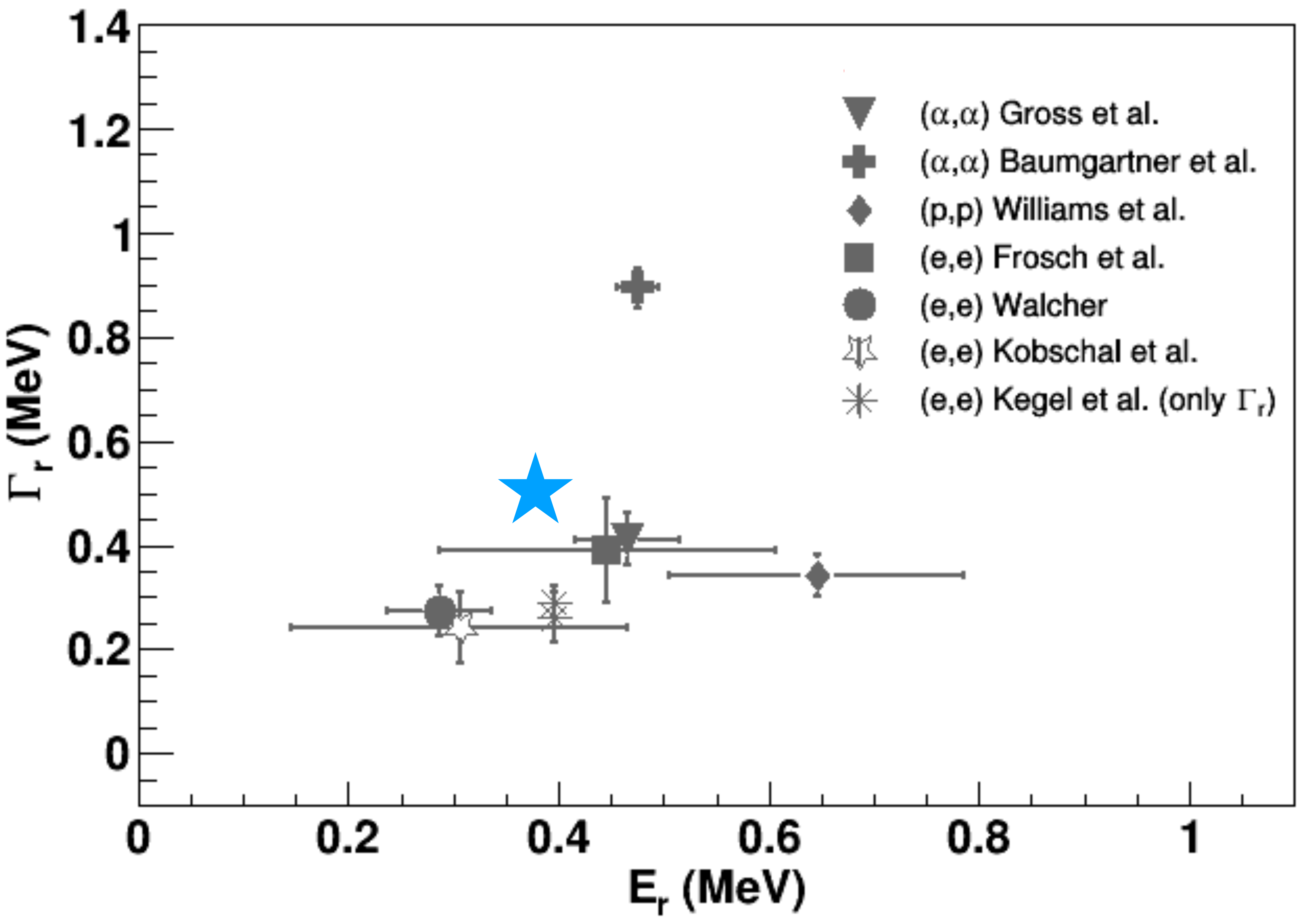
I don't think that we can yet close the chapter on this observable!

Resonance characterization: Th vs Exp



Resonance characterization: Exp only

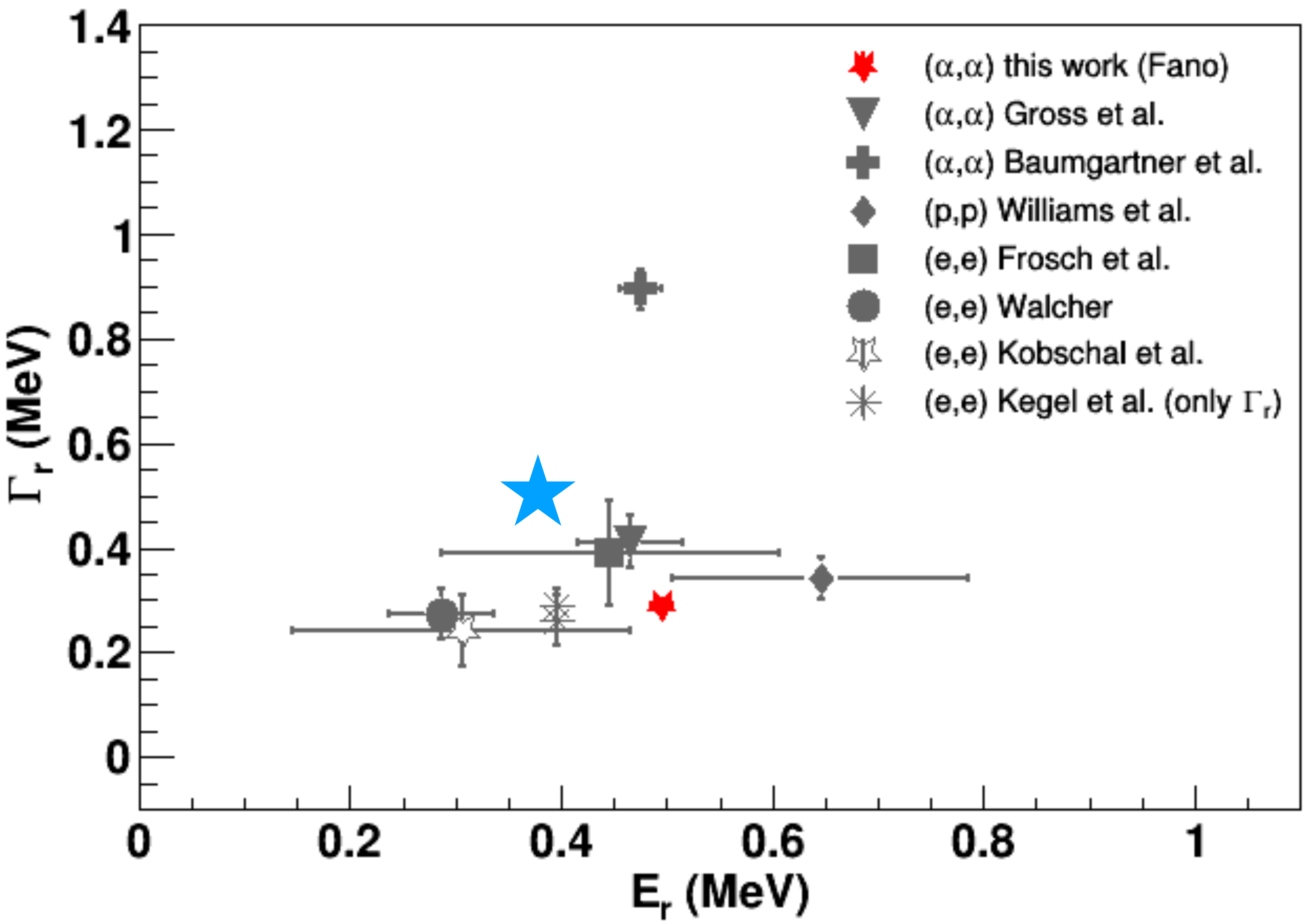
★ Evaluation by Tilley et al, NPA 541 (1992) 1-104



Resonance characterization: Exp only

New characterization via α-α scattering in Catania

Cappuzzello, Soukeras et al., to be submitted



Tilley et al $E_r = 0.39 \pm 0.02$ MeV, $\Gamma_r = 0.50 \pm 0.05$ MeV

New value $E_r = 0.50 \pm 0.01$ MeV, $\Gamma_r = 0.29 \pm 0.01$ MeV

Challenges

- What’s the role of the continuum?
- And of the resonance position?
- Why is there a strong Hamiltonian dependence?
- How precisely can we calculate resonance properties?

Supported by: PRISMA Cluster of Excellence; Hadrons Nuclei CRC 1660; MARIE CURIE ACTIONS; Alexander von Humboldt Stiftung/Foundation

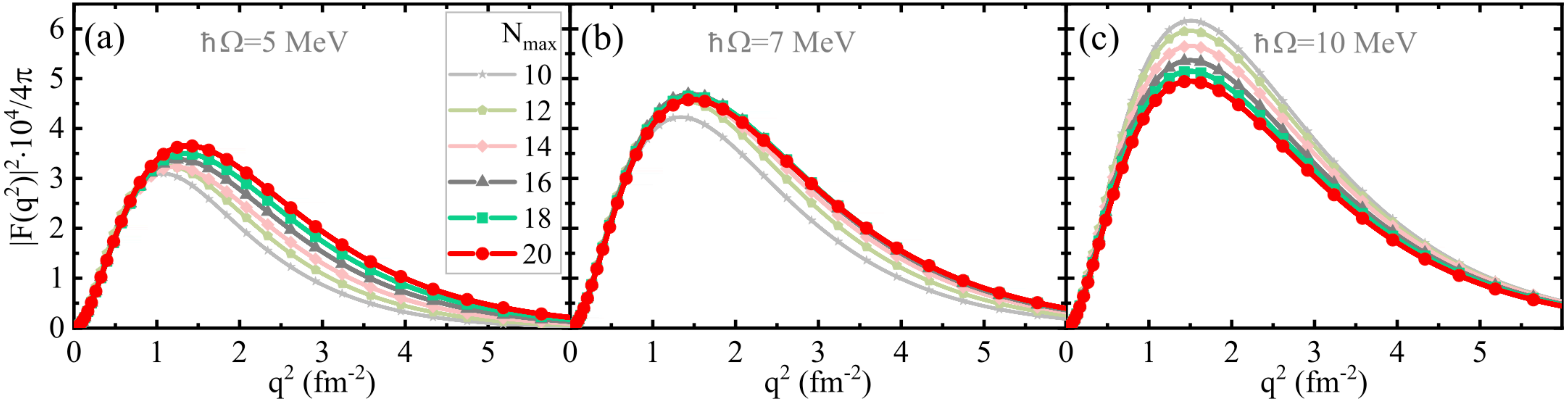
Thanks to all my collaborators

THANK YOU

Backup Slides

Additional info on other calculations

NCSM from P. Yin et al, 2412.18037



LIT + HH for the monopole transition $0_1^+ \to 0_2^+$

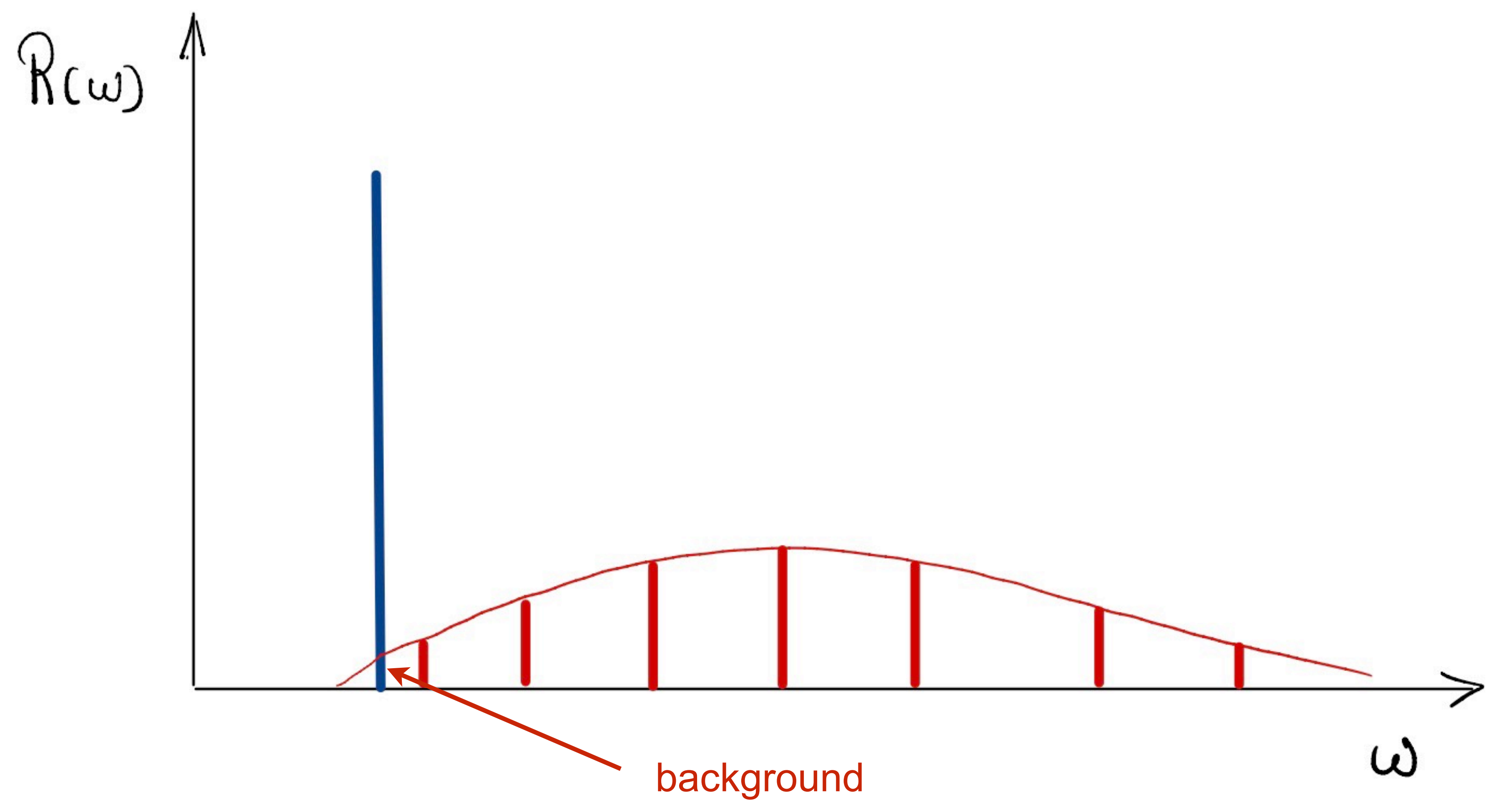
$$|F_{\mathcal{M}}(q)|^2 = \frac{1}{Z^2} \int d\omega R^{\rm res}_{\mathcal{M}}(q,\omega) \qquad R(q,\omega) = R^{\rm res}_{\mathcal{M}}(q,\omega) + R^{\rm bg}_{\mathcal{M}}(q,\omega)$$

For fixed *q*, apply integral transform

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

and solve bound-state-like equation
with hyperspherical harmonics (HH)

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



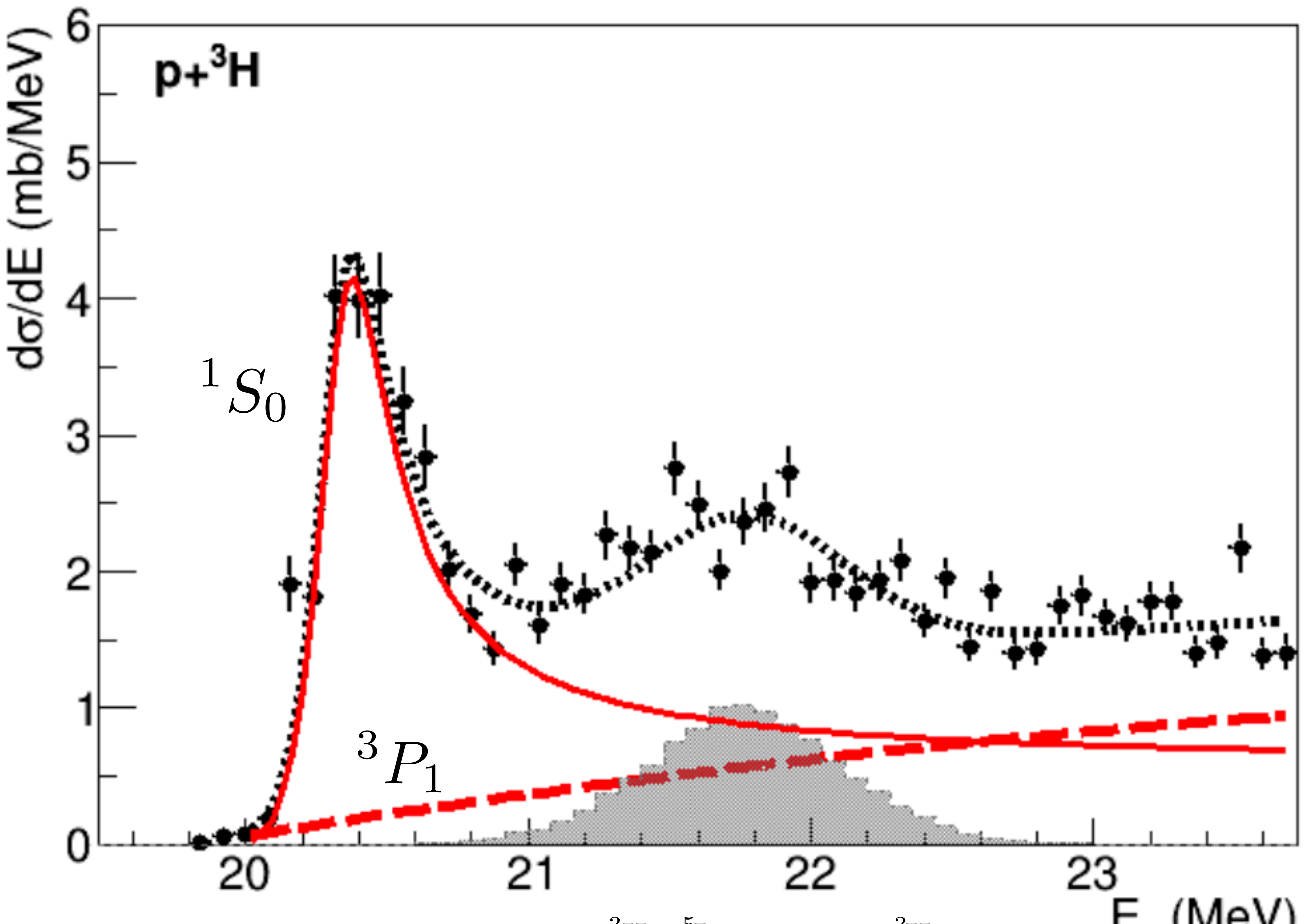
We see one pronounced peak at the resonant energy, and many others at higher energy
Exploit the power of the LIT method to subtract the background

New experiment: α-α scattering

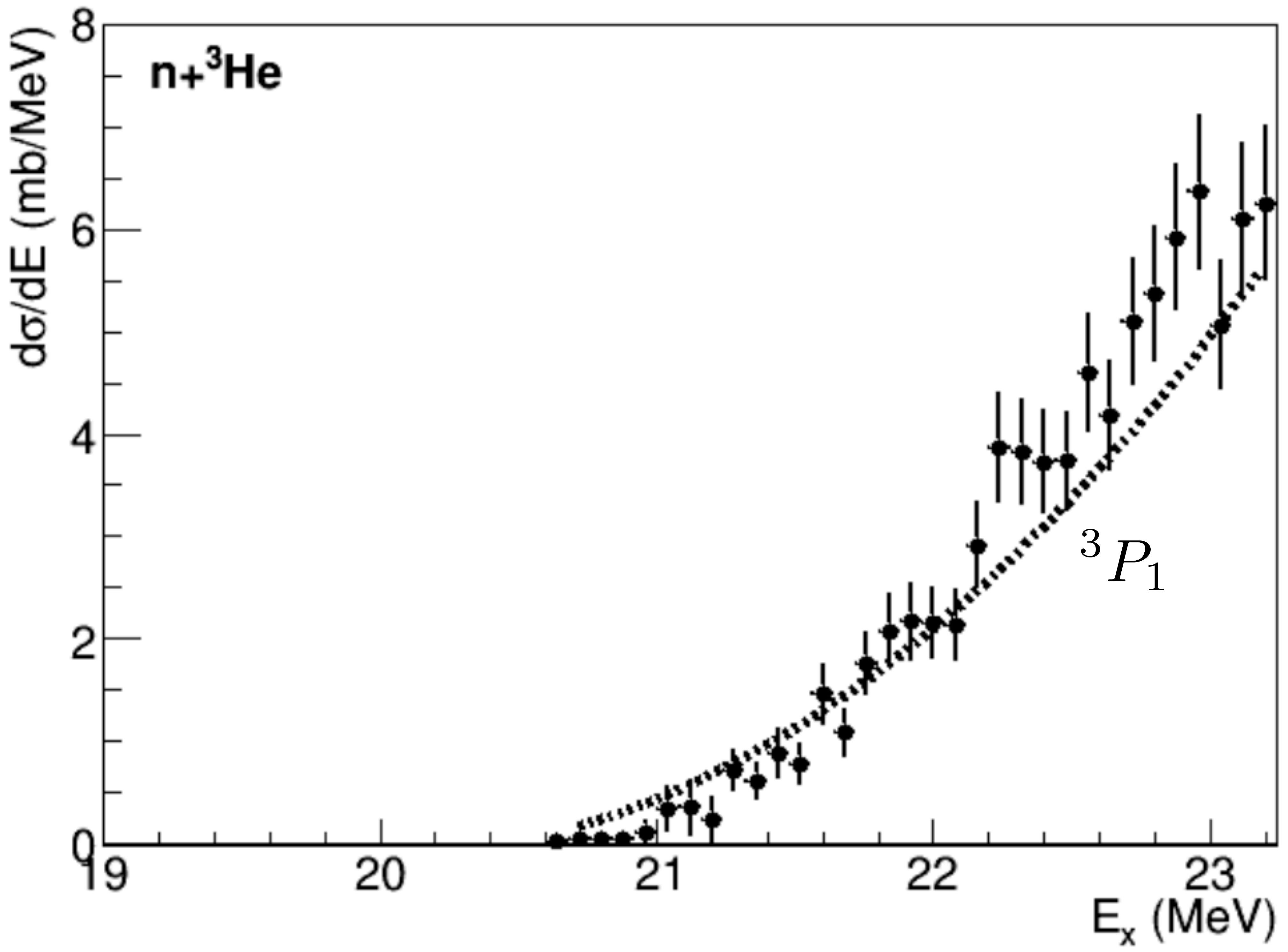
Catania

Experiment by Cappuzzello, Soukeras et al.

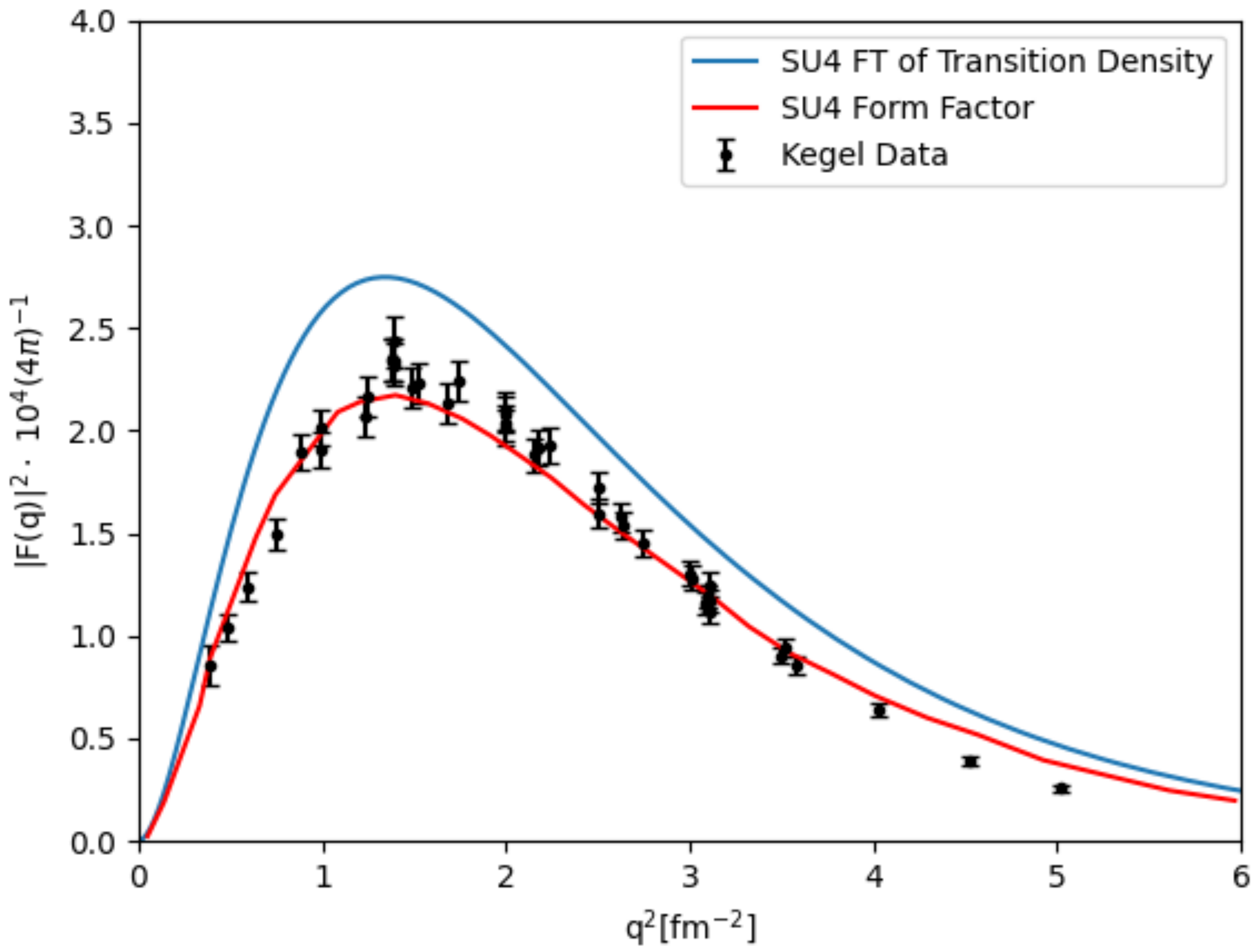
Fano analysis (accounts for asymmetries in the resonance)



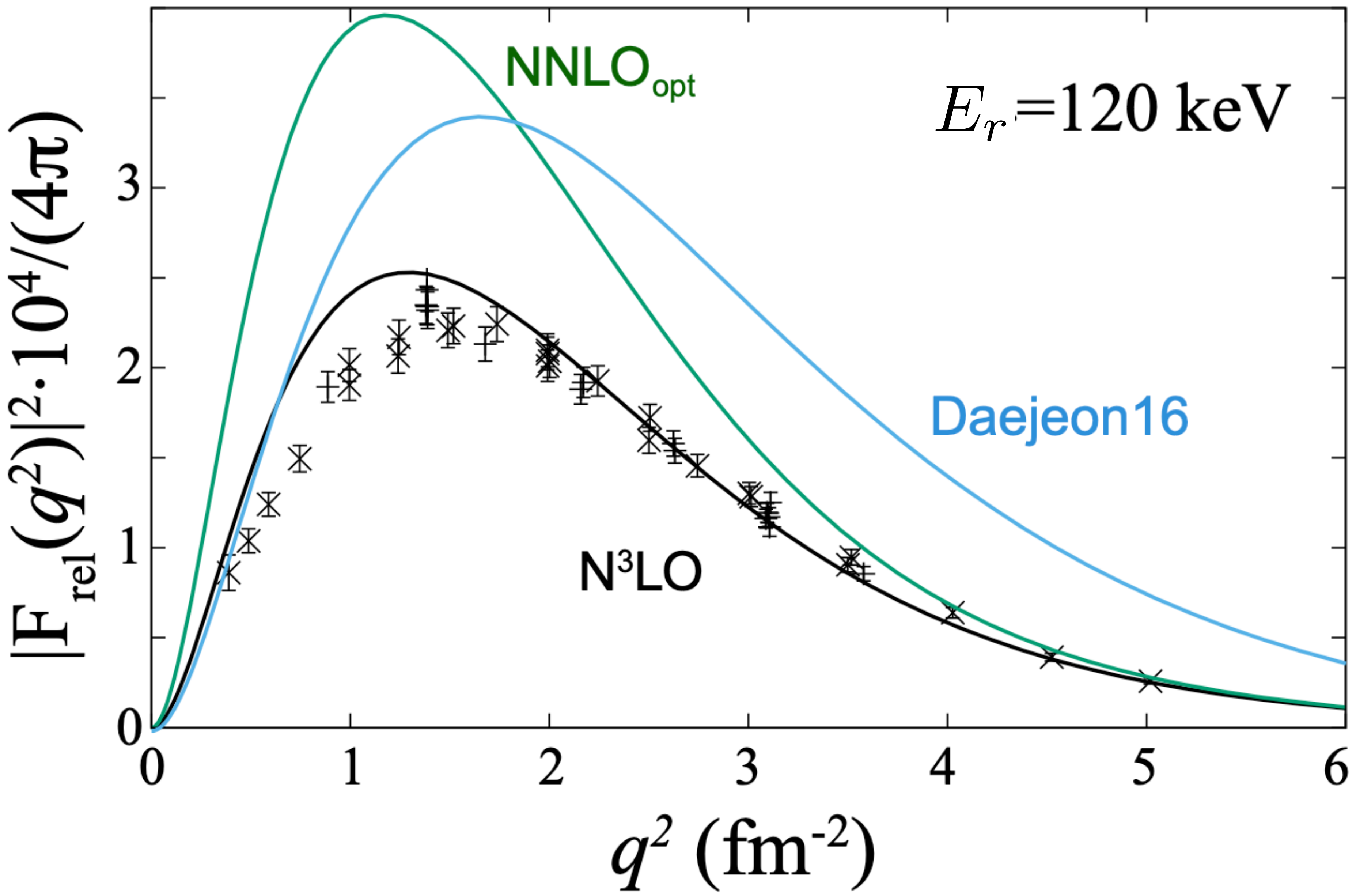
$\alpha + \alpha \to {}^3\mathrm{H} + {}^5\mathrm{Li} \to \alpha + p + {}^3\mathrm{H}$



Additional info on other calculations



Michel et al., Errata 2024

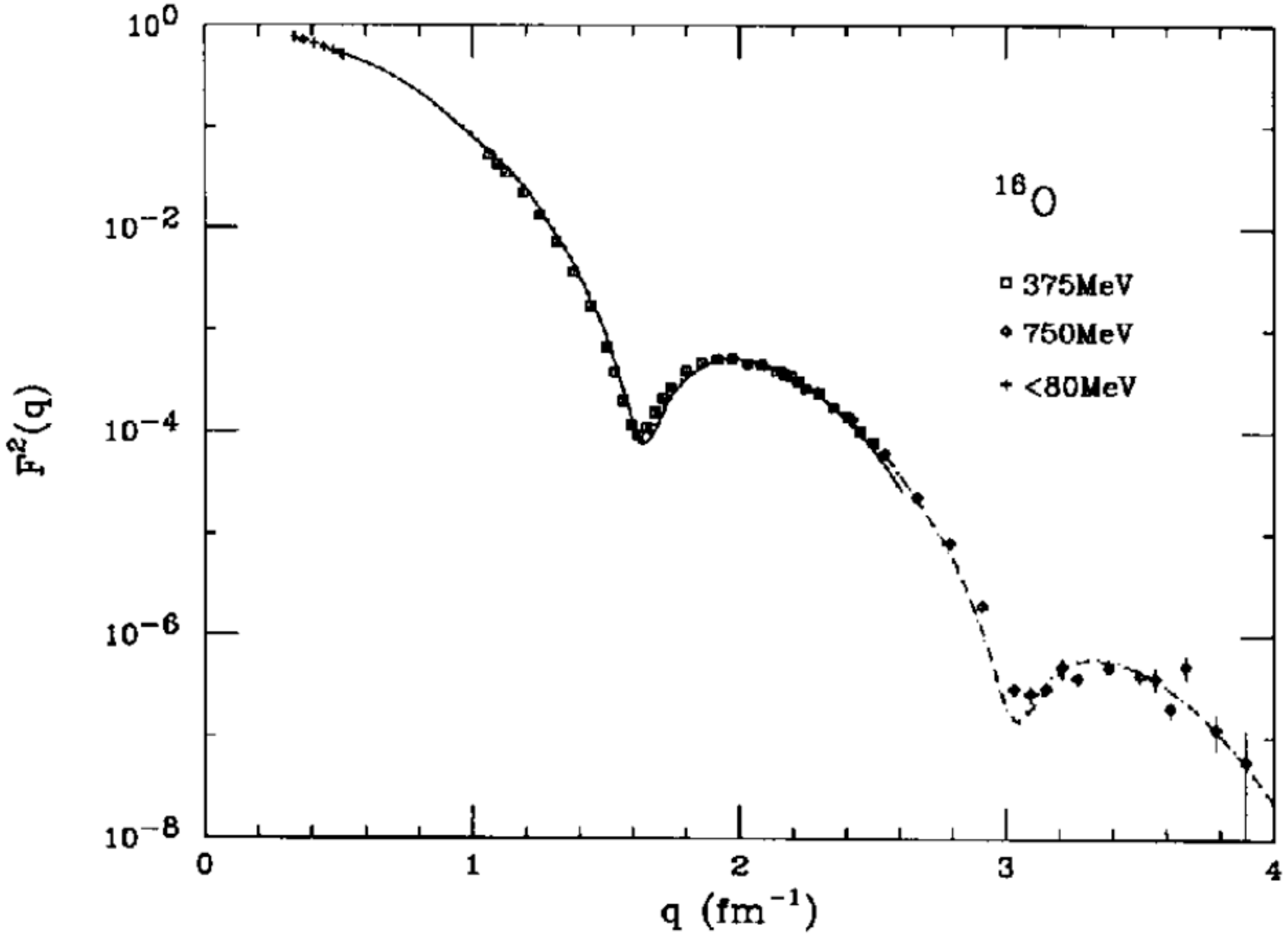


Large potential dependence is seen, consistent with our findings

Electron scattering

A cornerstone in nuclear structure

- Clean probe due to well-understood EM interaction
- Mapped charge distributions, radii, and EM excitations of nuclei
- Essential benchmarks for nuclear models/ theories

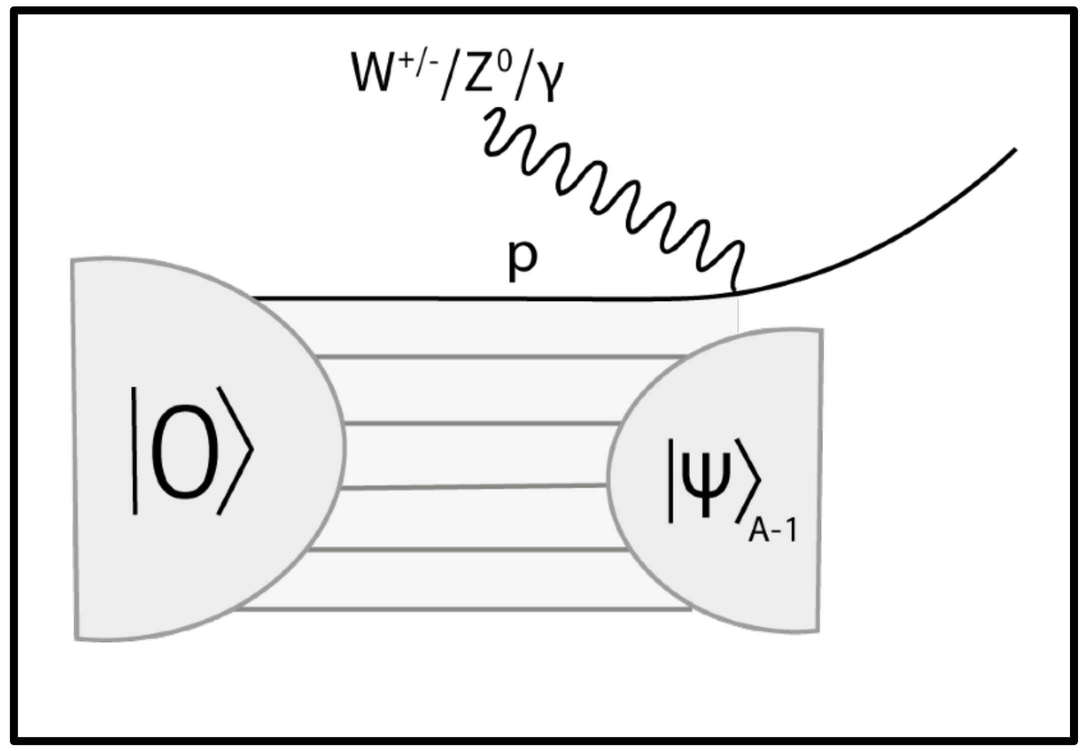


R. Hofstadter, "Electron Scattering and Nuclear Structure," *Rev. Mod. Phys.* **28**, 214 (1956).

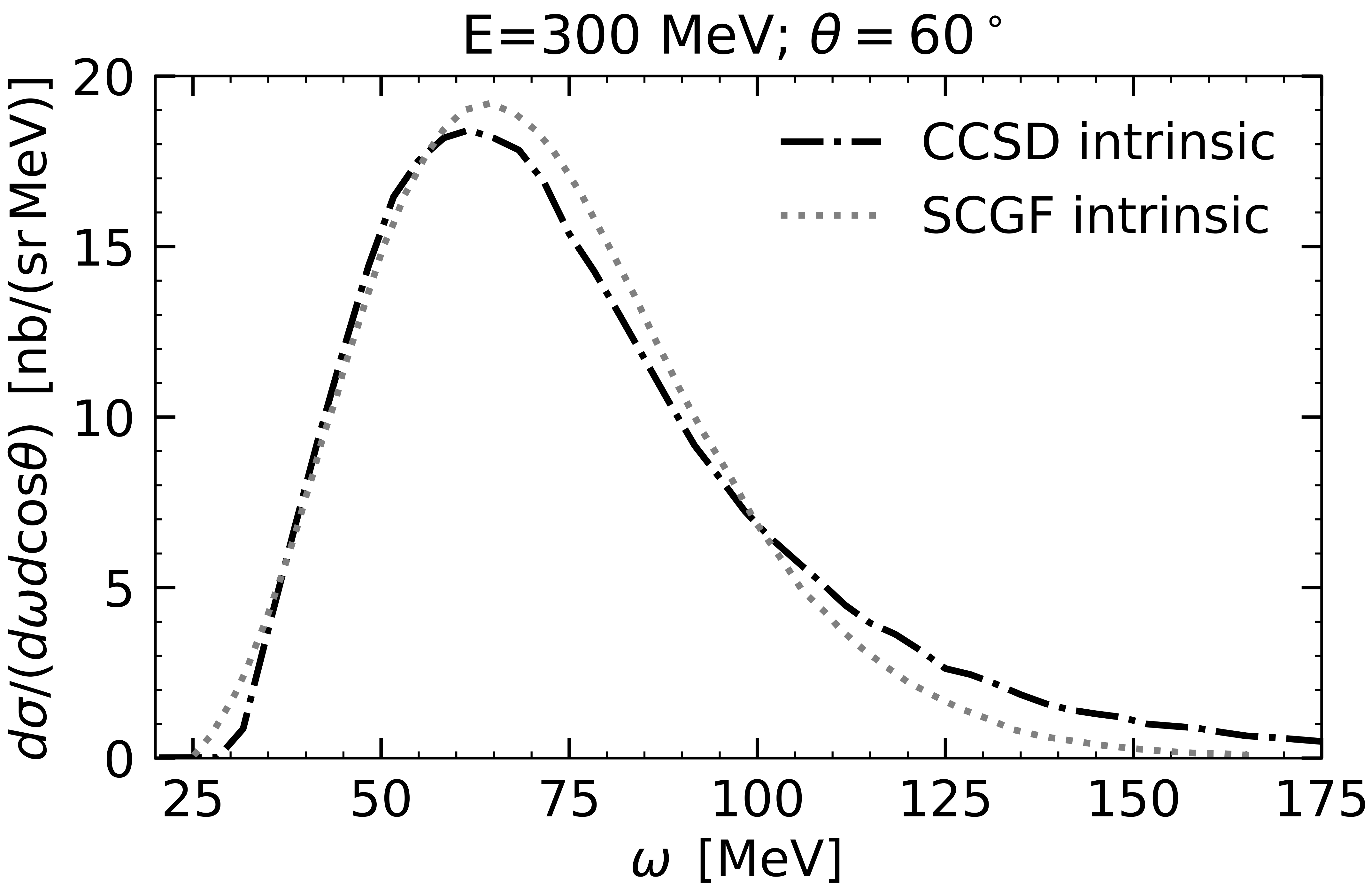
I. Sick, *Prog. Part. Nucl. Phys.* **47**, 245 (2001).

Electron scattering

Spectral function formalism for ^{4}He



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



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

Electron scattering

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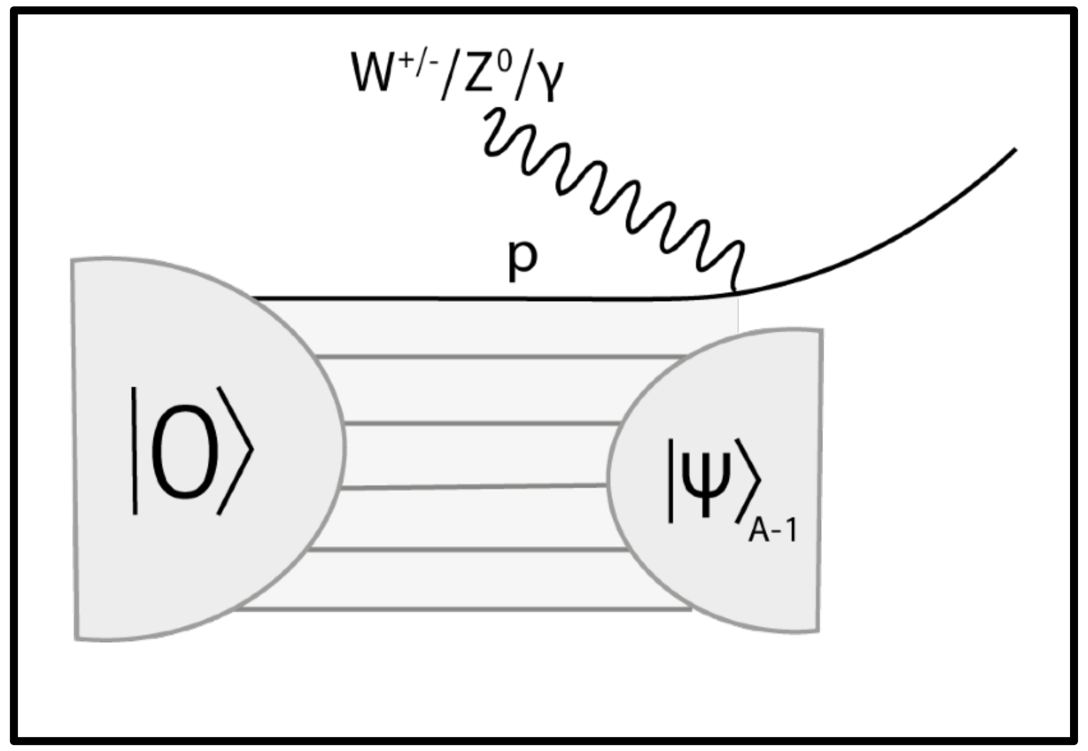
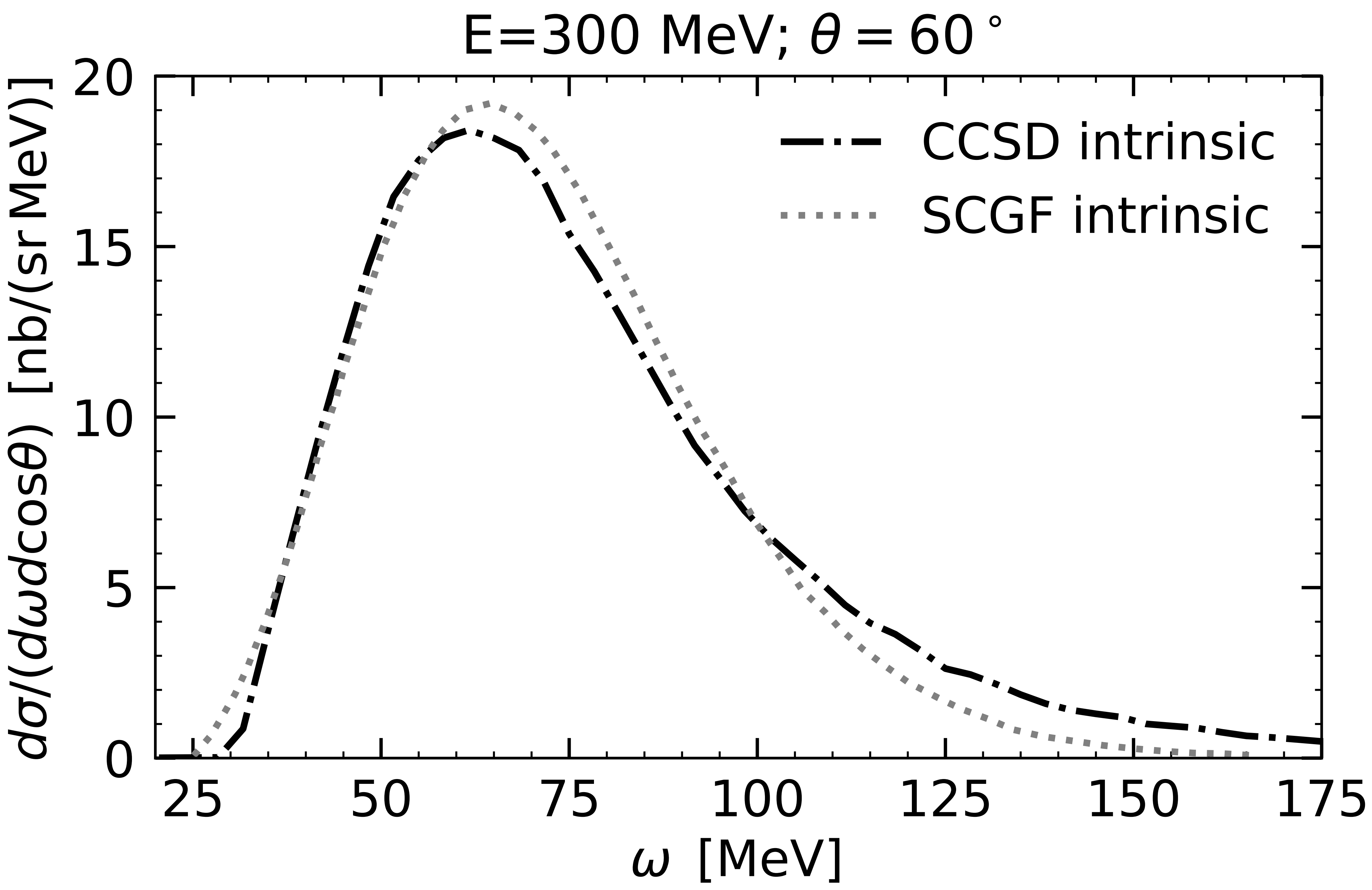
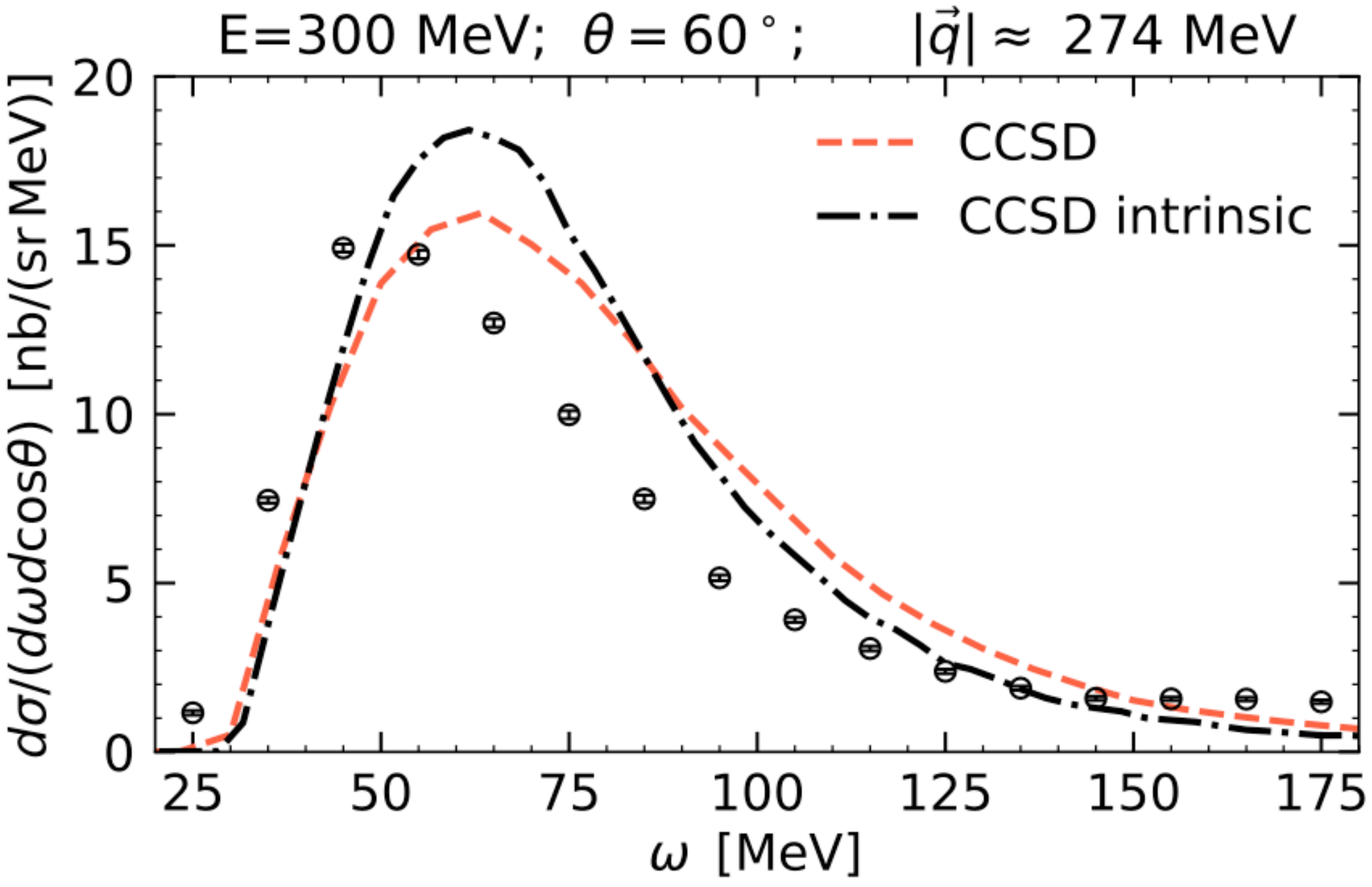


Sobczyk, SB, et al., PRC 106, 034310(2022)





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Electron scattering

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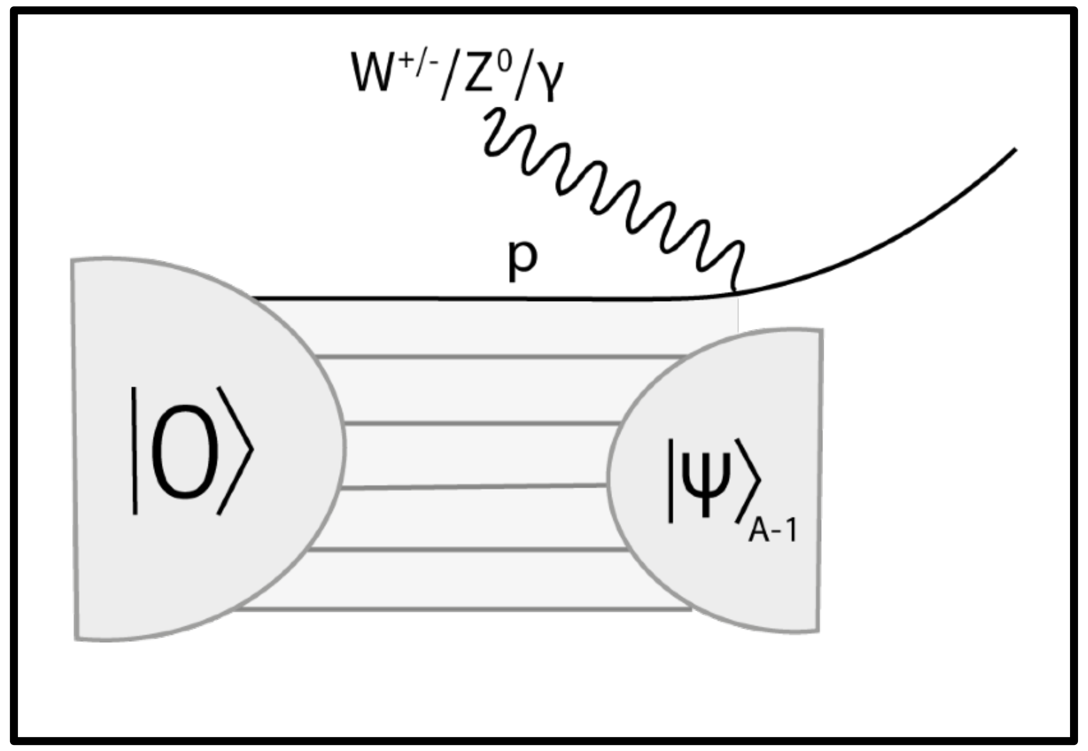

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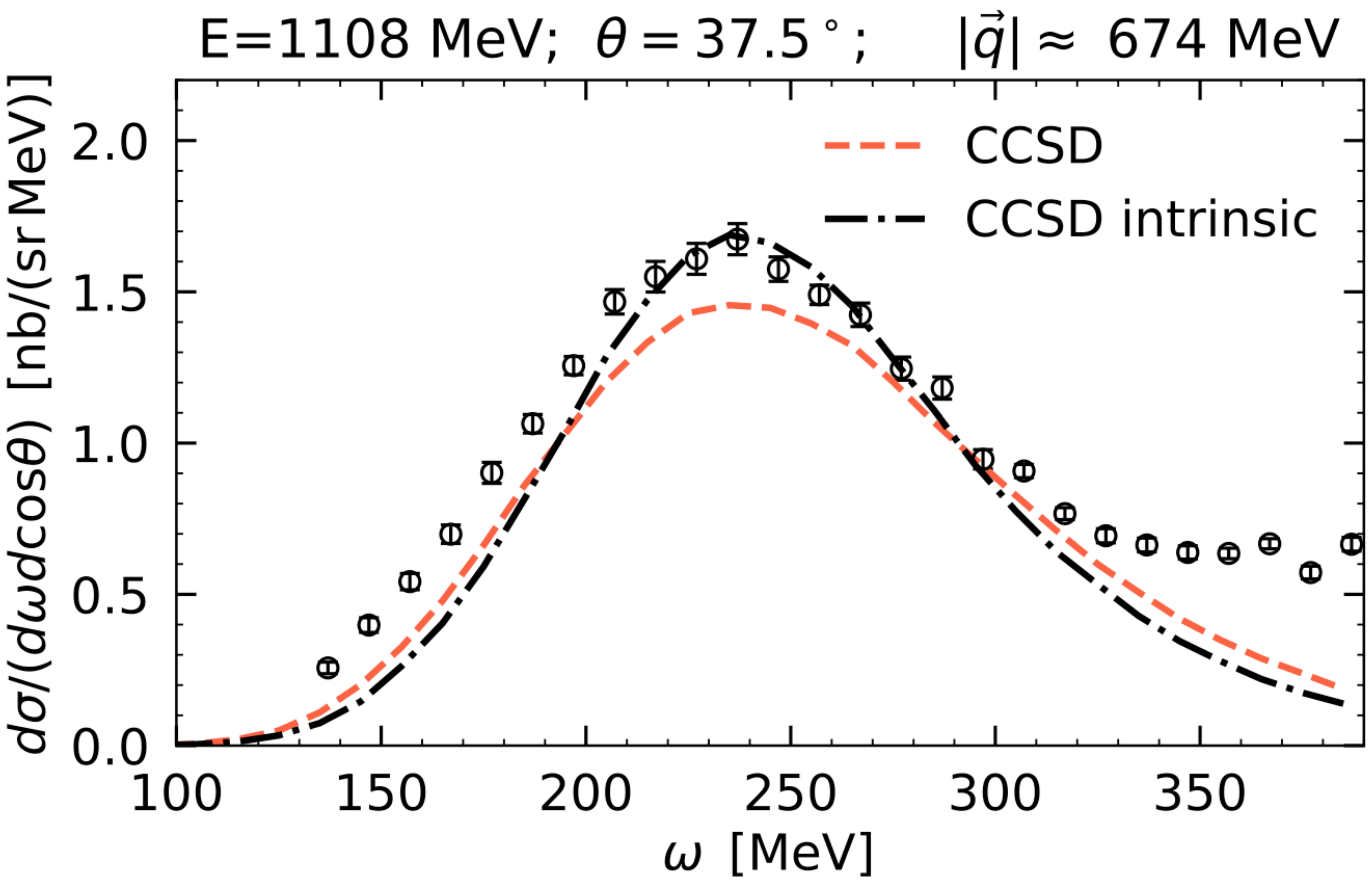
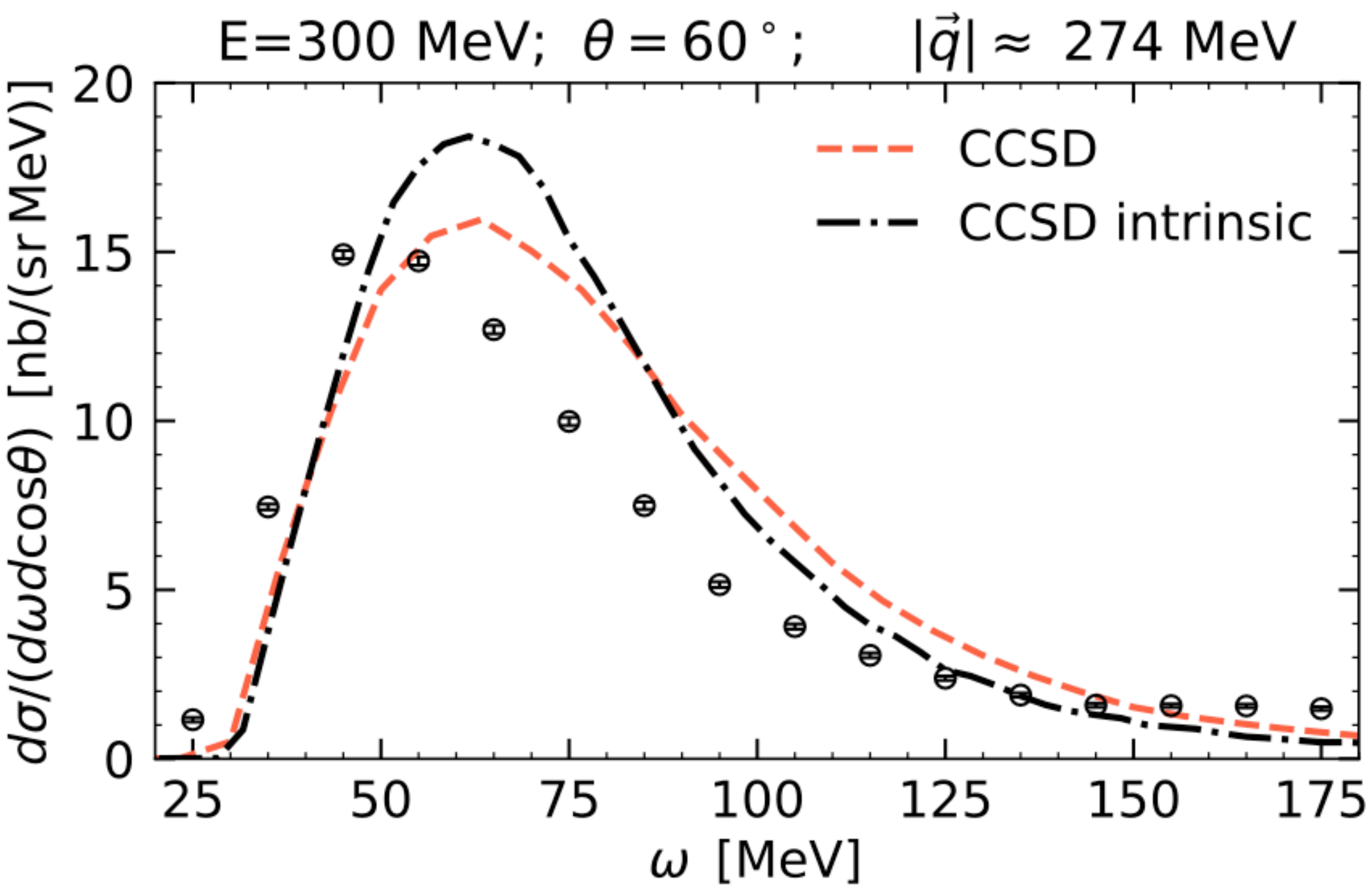
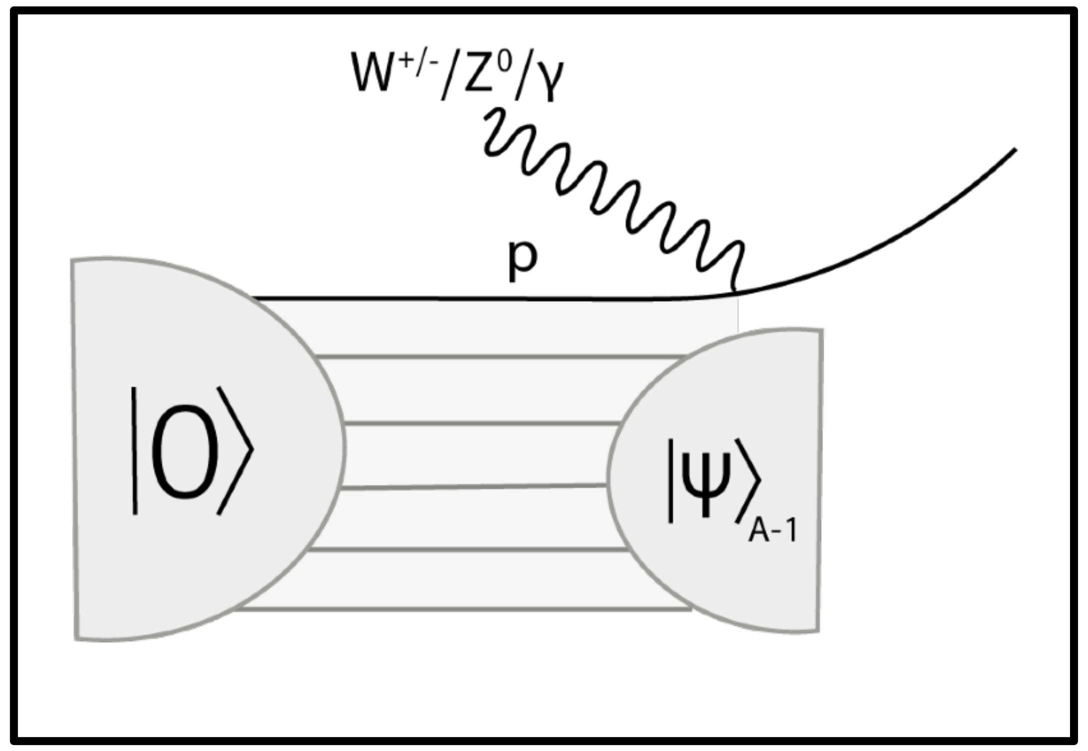




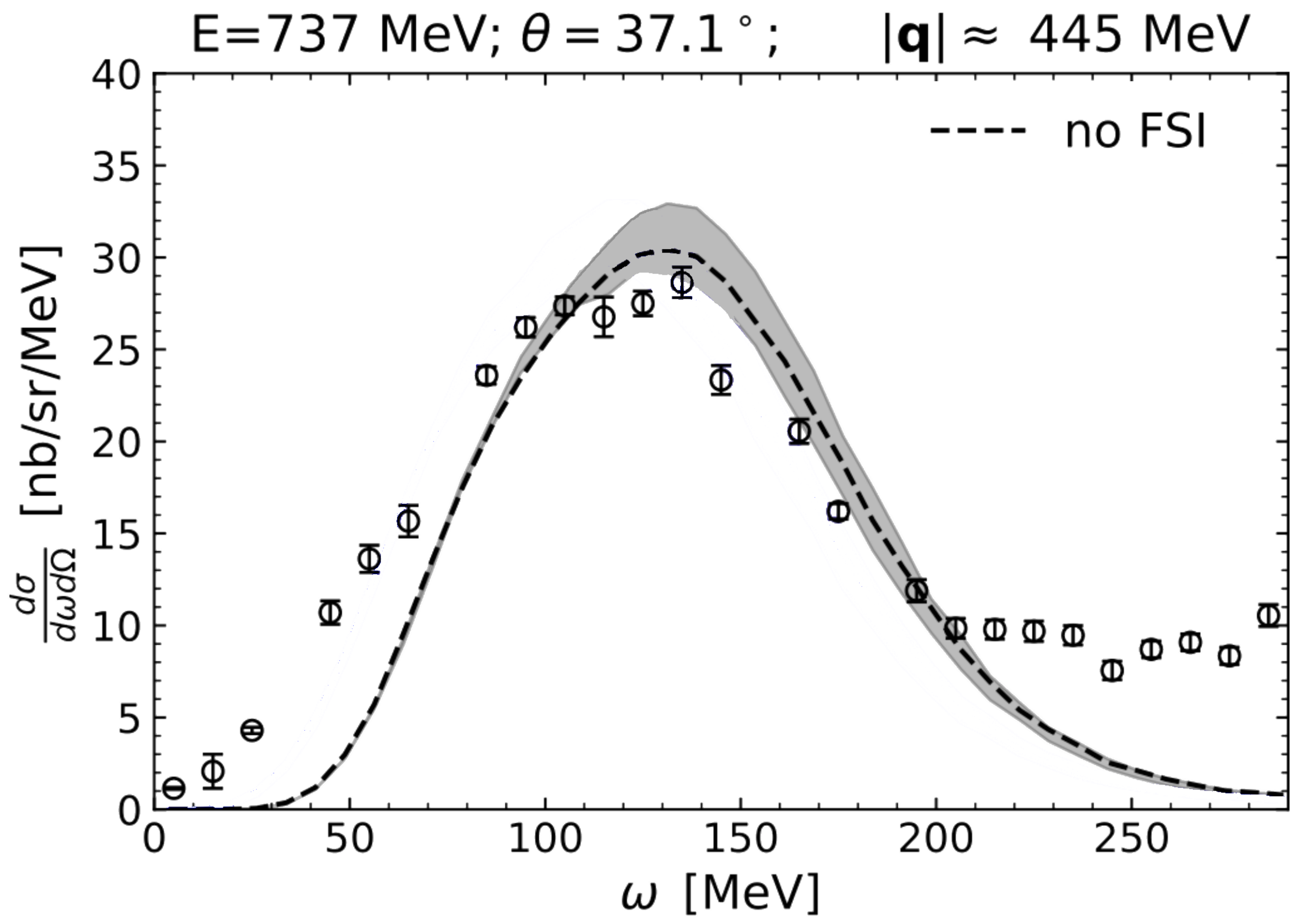
SF works at high-energy/high-momentum

Electron scattering

Spectral function formalism for ^{16}O

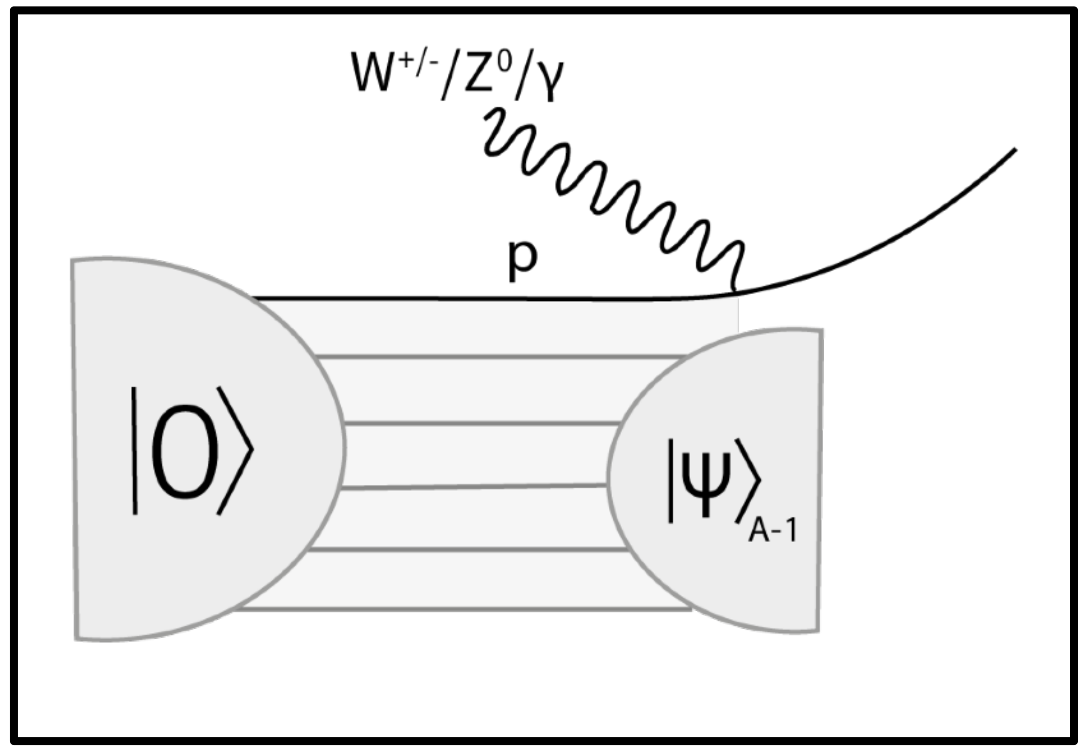


Sobczyk, SB, PRC 109, 044314 (2024)



Electron scattering

Spectral function formalism for ^{16}O



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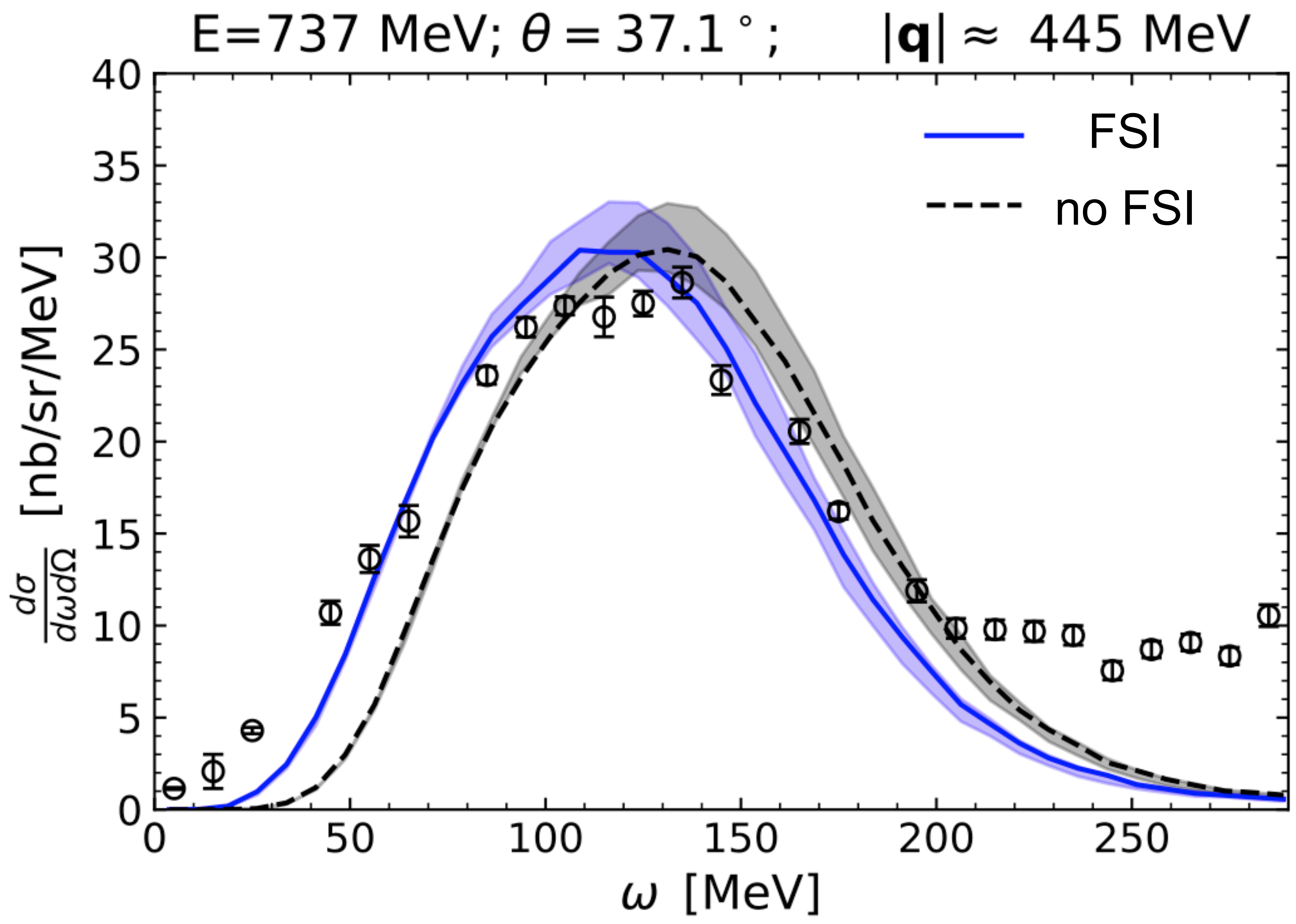
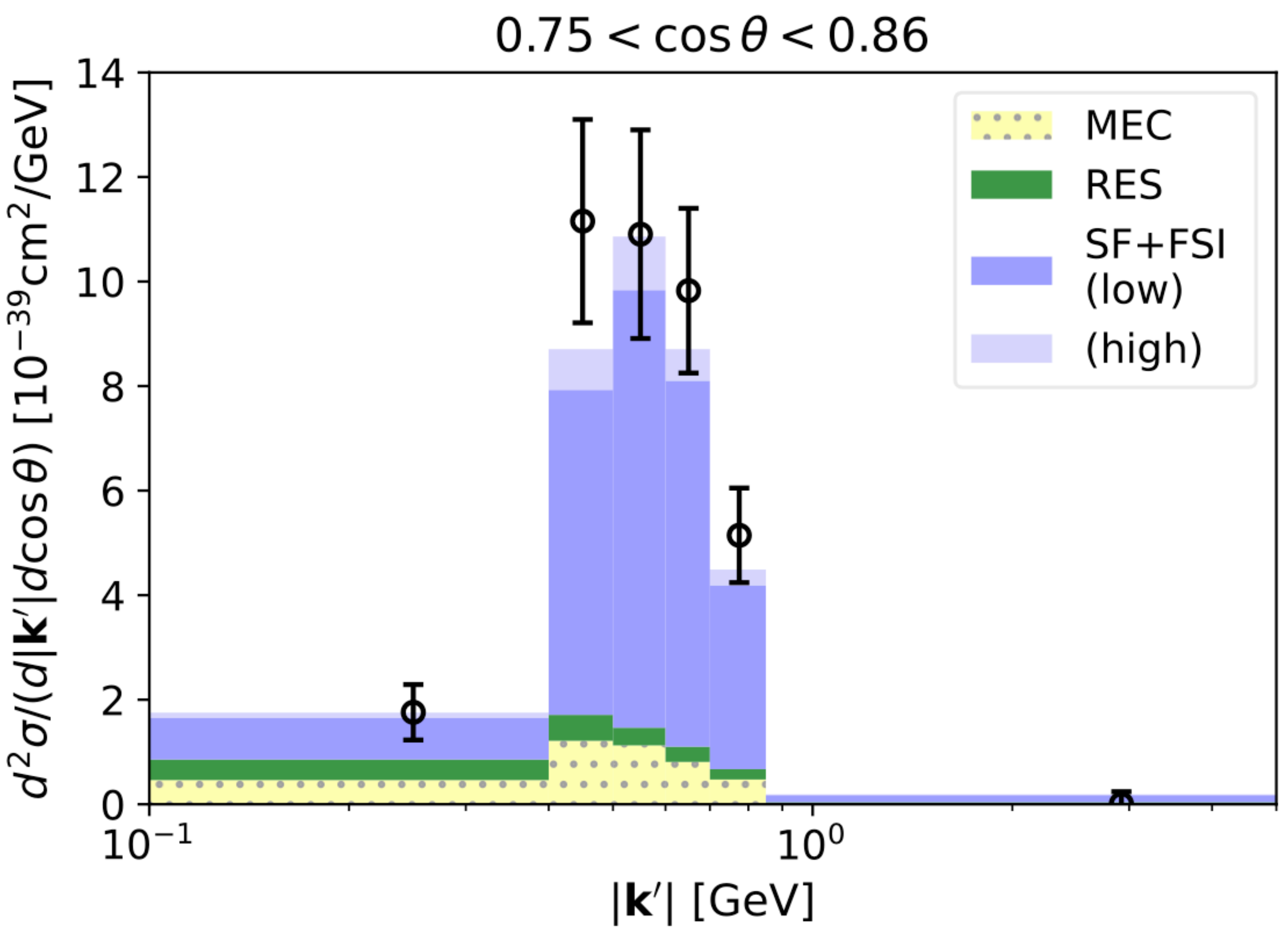


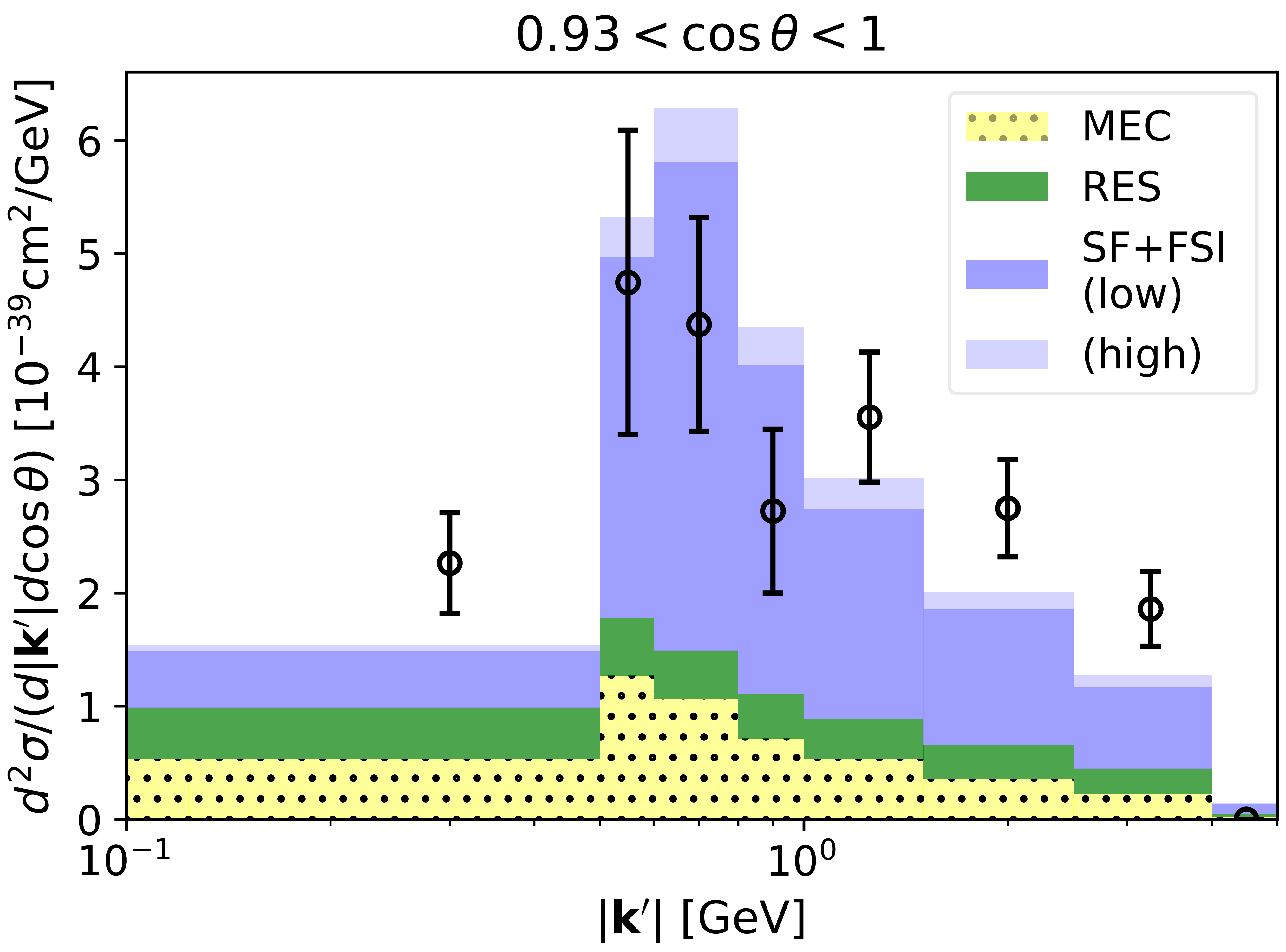
Towards neutrino scattering: T2K data

Spectral function formalism for ^{16}O

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

Sobczyk, SB, PRC 109, 044314 (2024)





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

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