Ab initio electroweak reactions with nuclei

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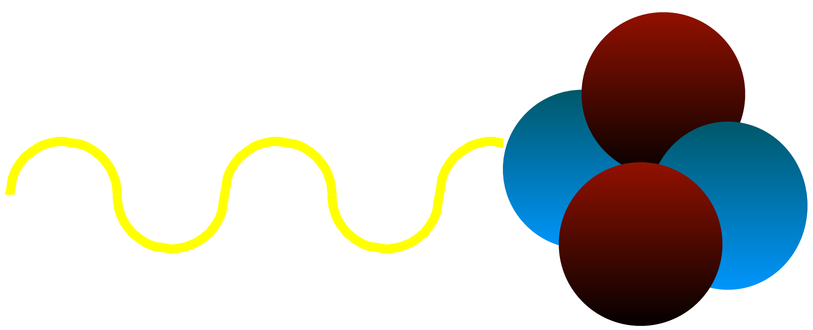
TRIUMF Workshop on "Progress in ab initio nuclear theory"

PRiSMA Cluster of Excellence   SFB 1245   MARIE CURIE ACTIONS   Alexander von Humboldt Stiftung/Foundation +

Electroweak reactions

arXiv:2212.11064

Ab initio calculation: systematically improvable approach for quantitatively describing nuclei using the finest resolution scale possible while maximizing its predictive capabilities.



Cross Section

$$\sigma_{ew} \sim R(\omega) = \sum\!\!\!\!\!\!\!\int_f \left| \left\langle \psi_f \middle| \Theta \middle| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$$

Electroweak operator

Integral Transforms

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

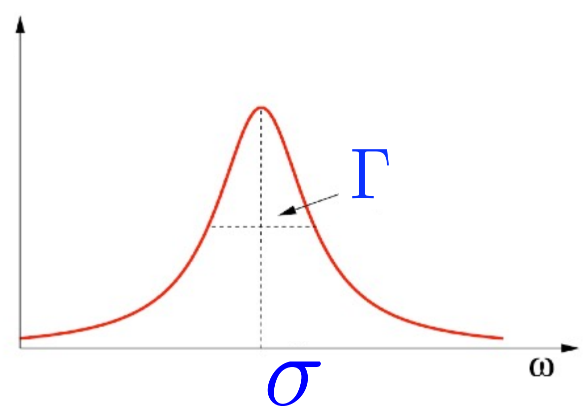
Exact knowledge limited in
energy and mass number

inversion

Lorentz Integral Transform

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

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



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

Reduce the continuum problem to a bound-state-like equation

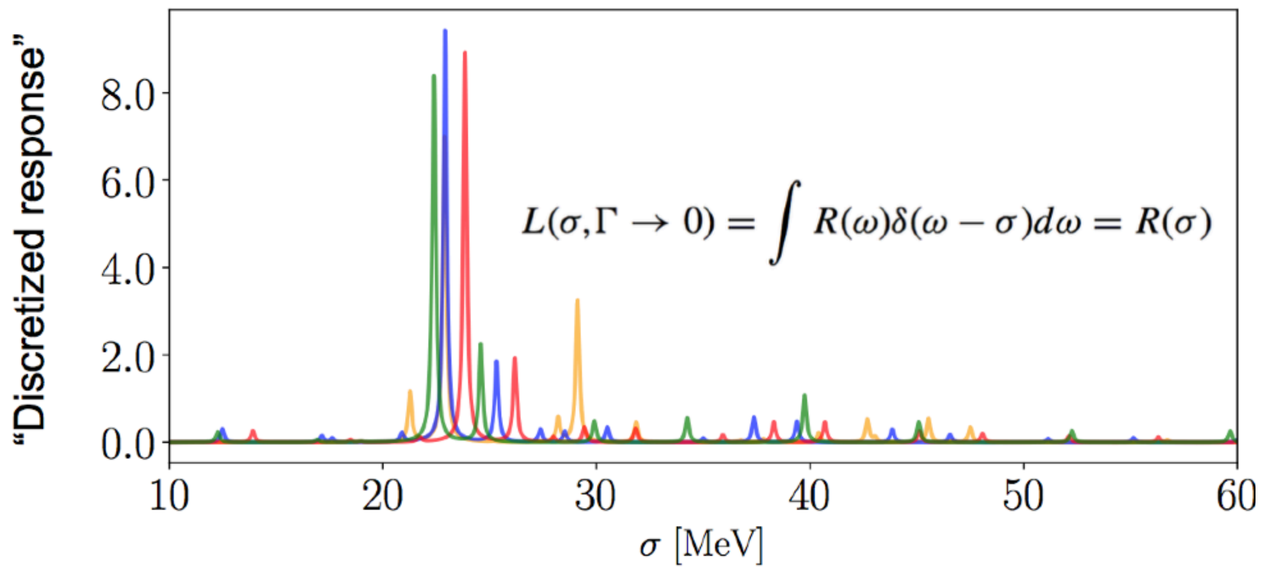
Sum Rules

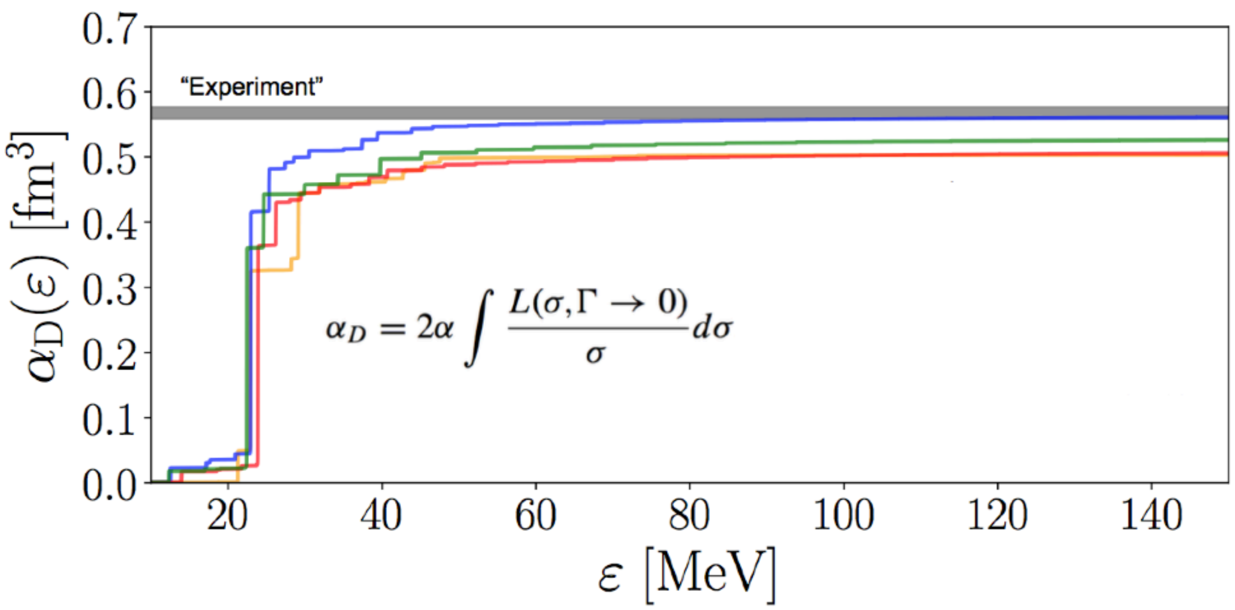
$$m_n = \int_0^\infty d\omega\ \omega^n R(\omega) = \langle \Psi_0 | \hat{\Theta}^\dagger (\hat{H} - E_0)^n \hat{\Theta} | \Psi_0 \rangle$$

The polarizability is an inverse-energy weighted sum rule of the dipole response function

$$\alpha_D = 2\ \alpha\ m_{-1} = 2\ \alpha\ \langle \Psi_0 | \Theta^\dagger \frac{1}{(H - E_0)} \Theta | \Psi_0 \rangle$$

Can be obtained from the Lorentz Integral Transform in the limit of $\Gamma \rightarrow 0$

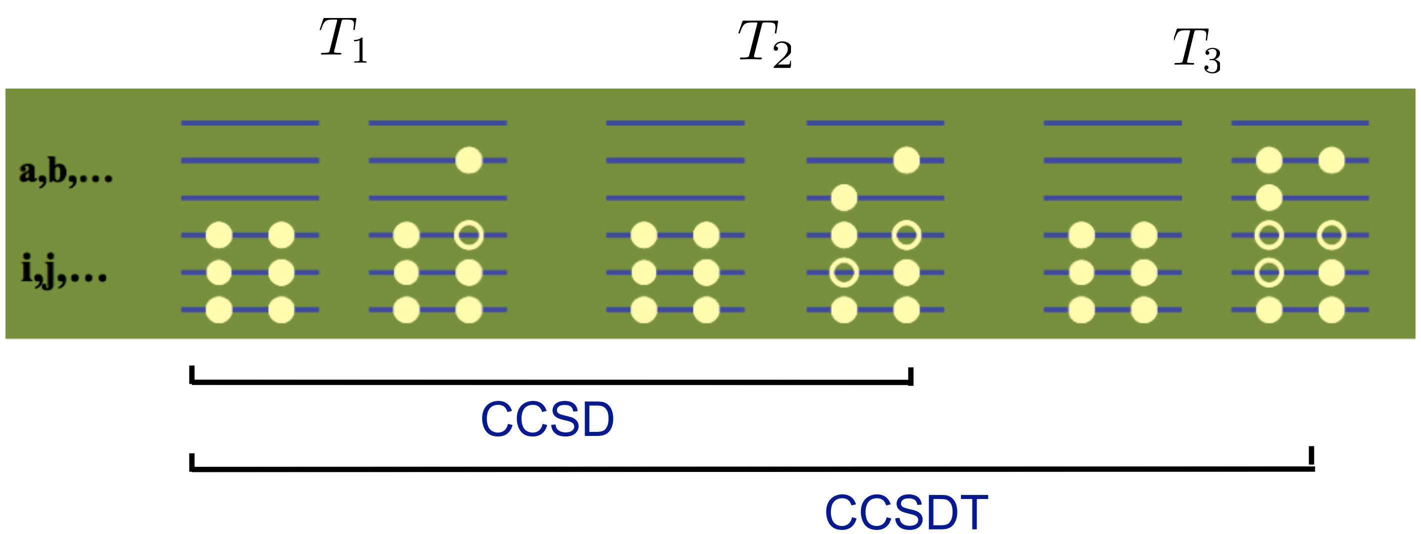




Coupled-cluster theory formulation

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

cluster expansion



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

$$(\bar{H} - E_0 - \sigma + i\Gamma)|\tilde{\Psi}_R\rangle = \bar{\Theta}|\Phi_0\rangle \quad \rightarrow \quad \begin{cases} \bar{H} = e^{-T} H e^{T} \\ \bar{\Theta} = e^{-T} \Theta e^{T} \\ |\tilde{\Psi}_R\rangle = \hat{R}|\Phi_0\rangle \end{cases}$$

$$\mathcal{R}(z) = r_0(z) + \sum_{ai} r_i^a(z) a_a^\dagger a_i + \frac{1}{4}\sum_{abij} r_{ij}^{ab}(z) a_a^\dagger a_b^\dagger a_j a_i + ...$$

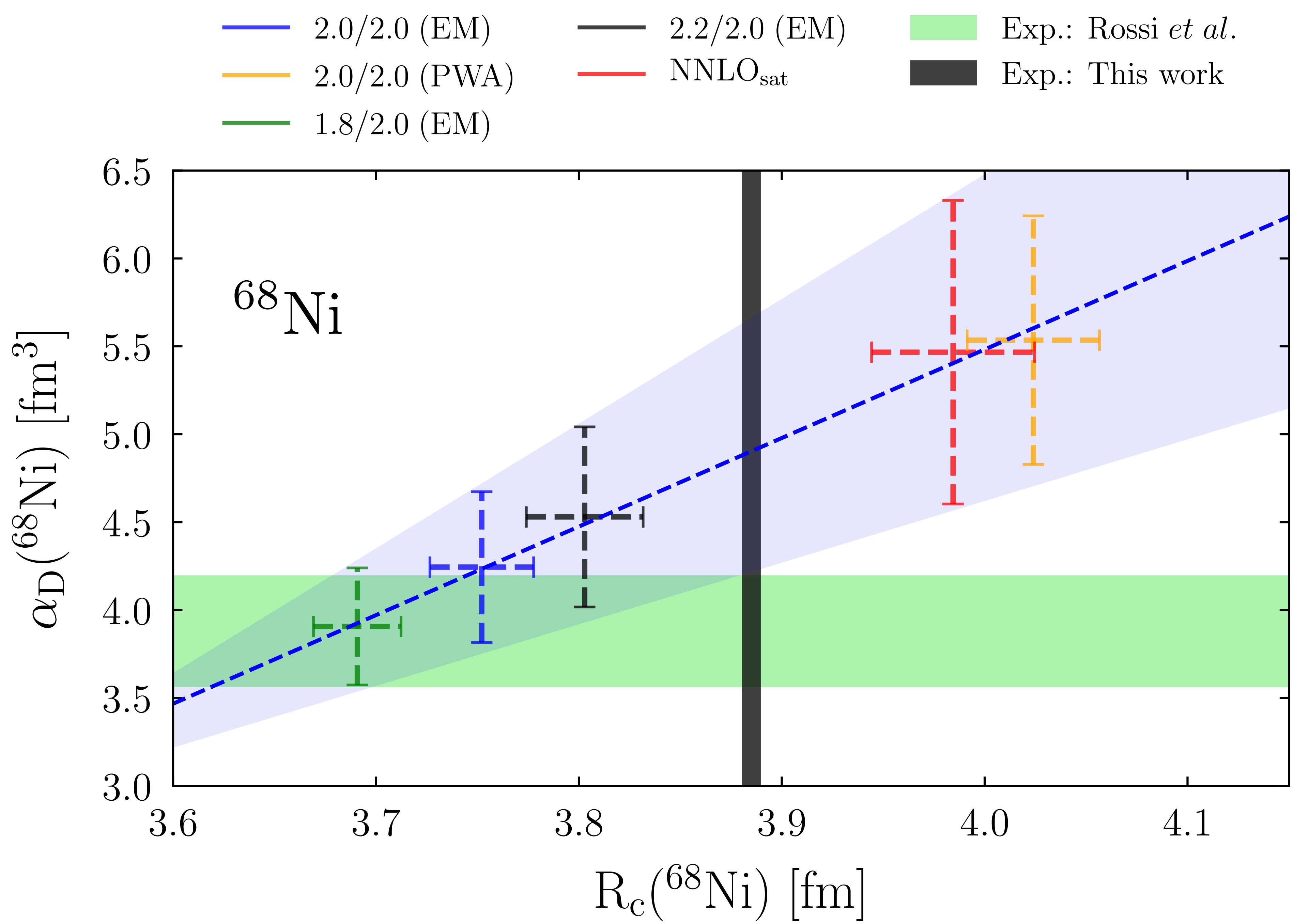
Results with implementation at CCSD level + some study of triples contributions

Title Text

Electric Dipole Polarizability

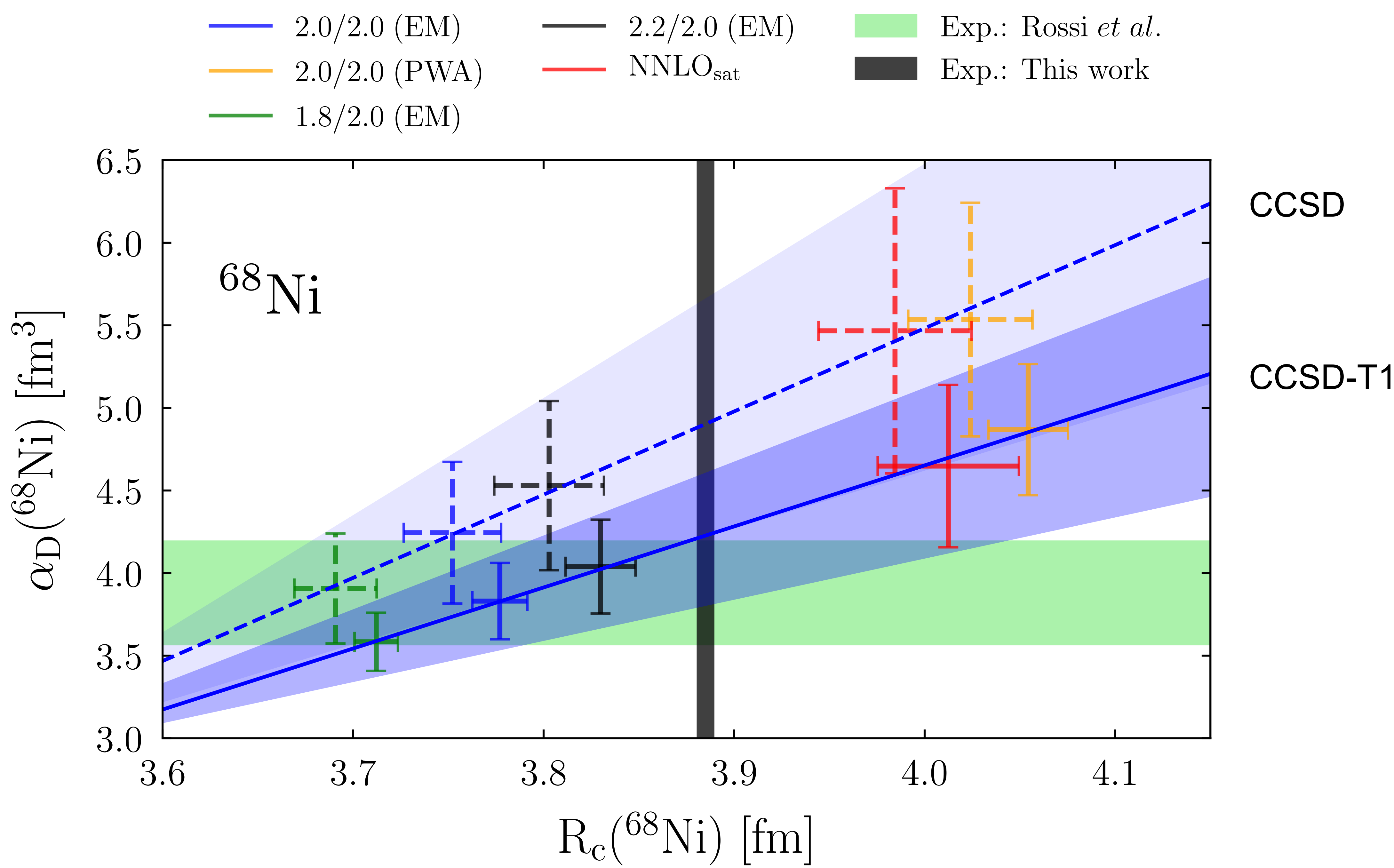
The ^{68}Ni nucleus

S.Kaufmann, J. Simonis, SB *et al.*, PRL **104** (2020) 132505



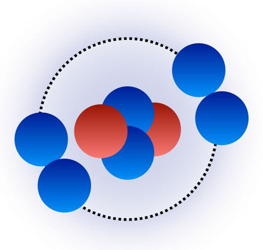
The ^{68}Ni nucleus

S.Kaufmann, J. Simonis, SB *et al.*, PRL **104** (2020) 132505



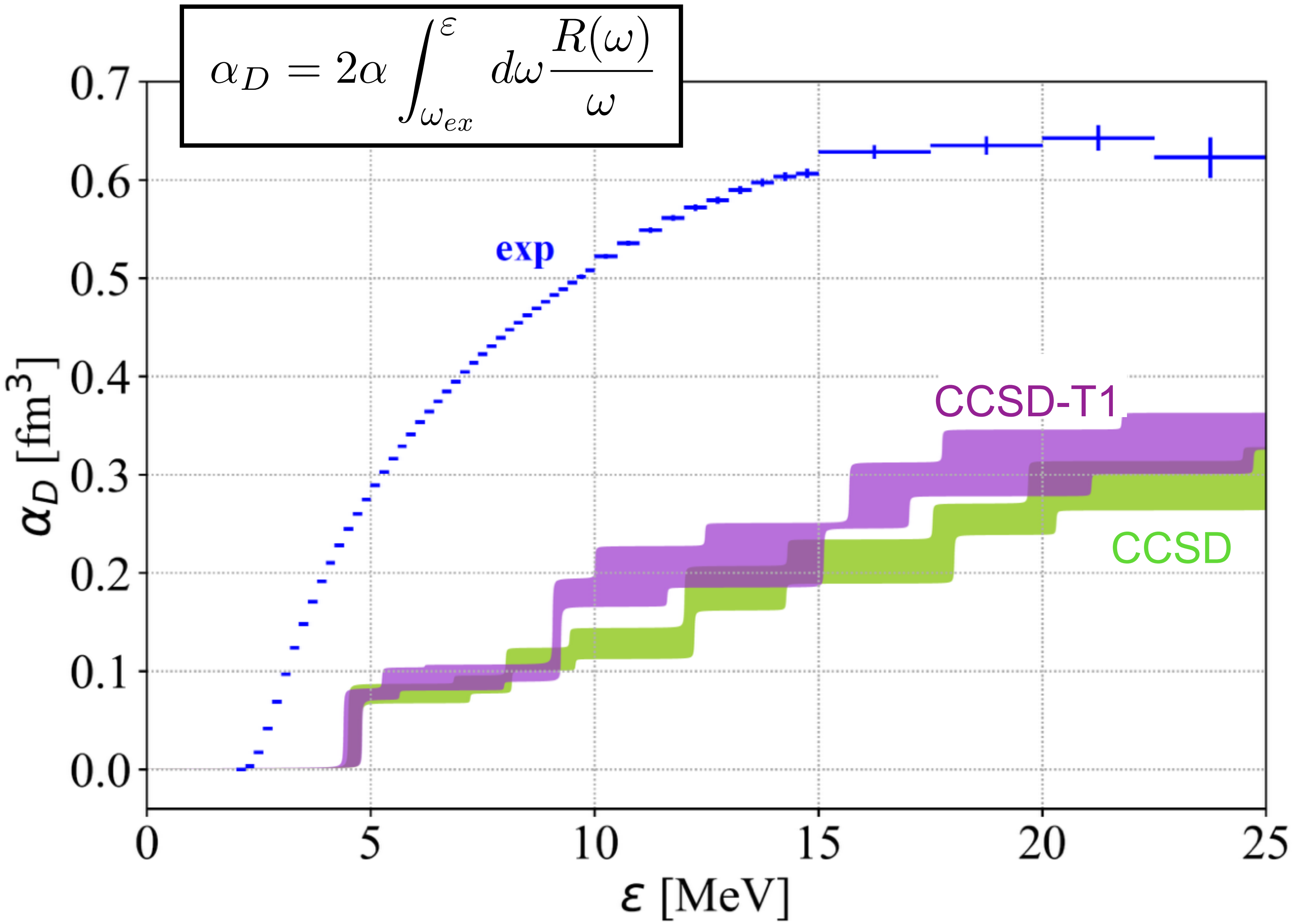
Halo nuclei

^{8}He



Electric dipole polarizability

F. Bonaiti, SB, G.Hagen, PRC 105, 034313 (2022)

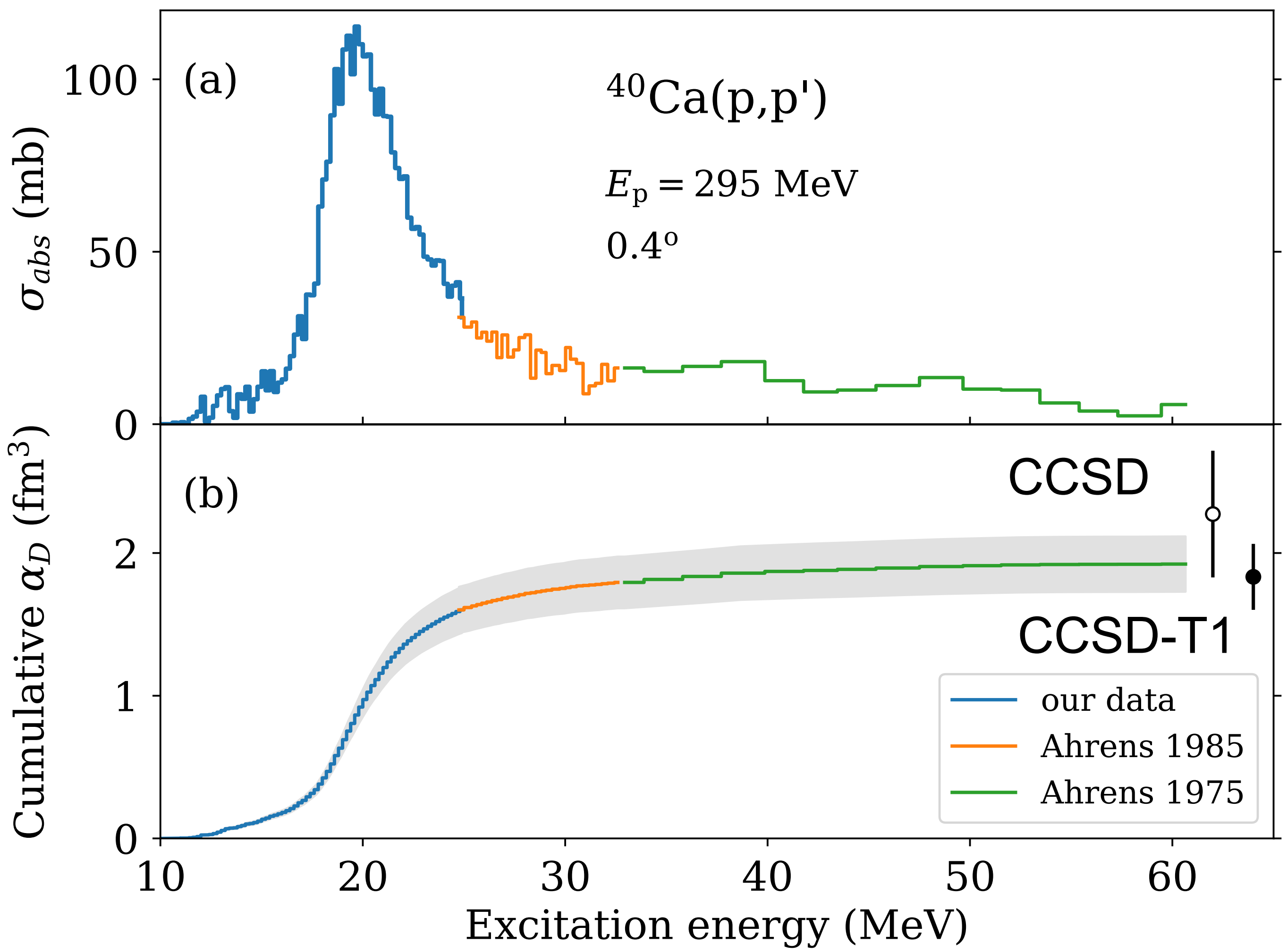


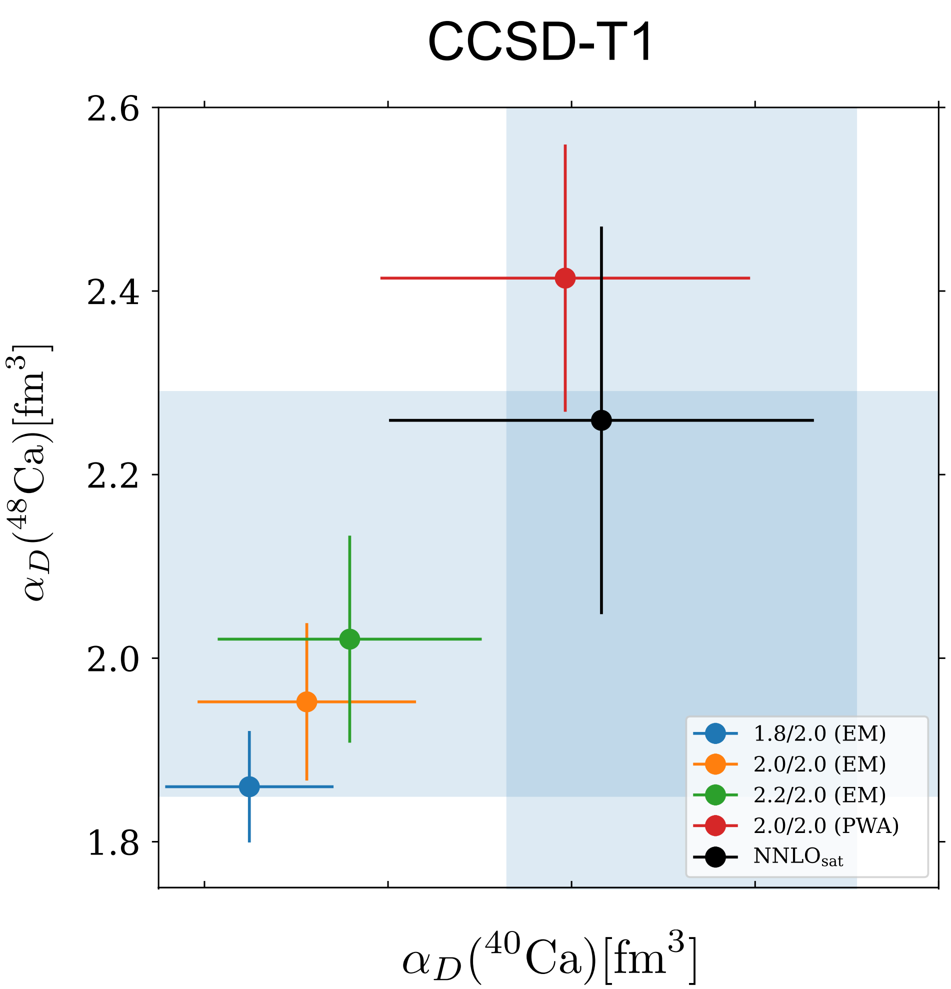
Exp (preliminary)
C. Lehr et al.
SAMURAI
collaboration

Theory:
brand spanning
$NNLO_{sat}$
$\Delta NNLO_{GO}$

The ^{40}Ca nucleus

Fearick, von Neumann-Cosel, SB et al, 2302.07490



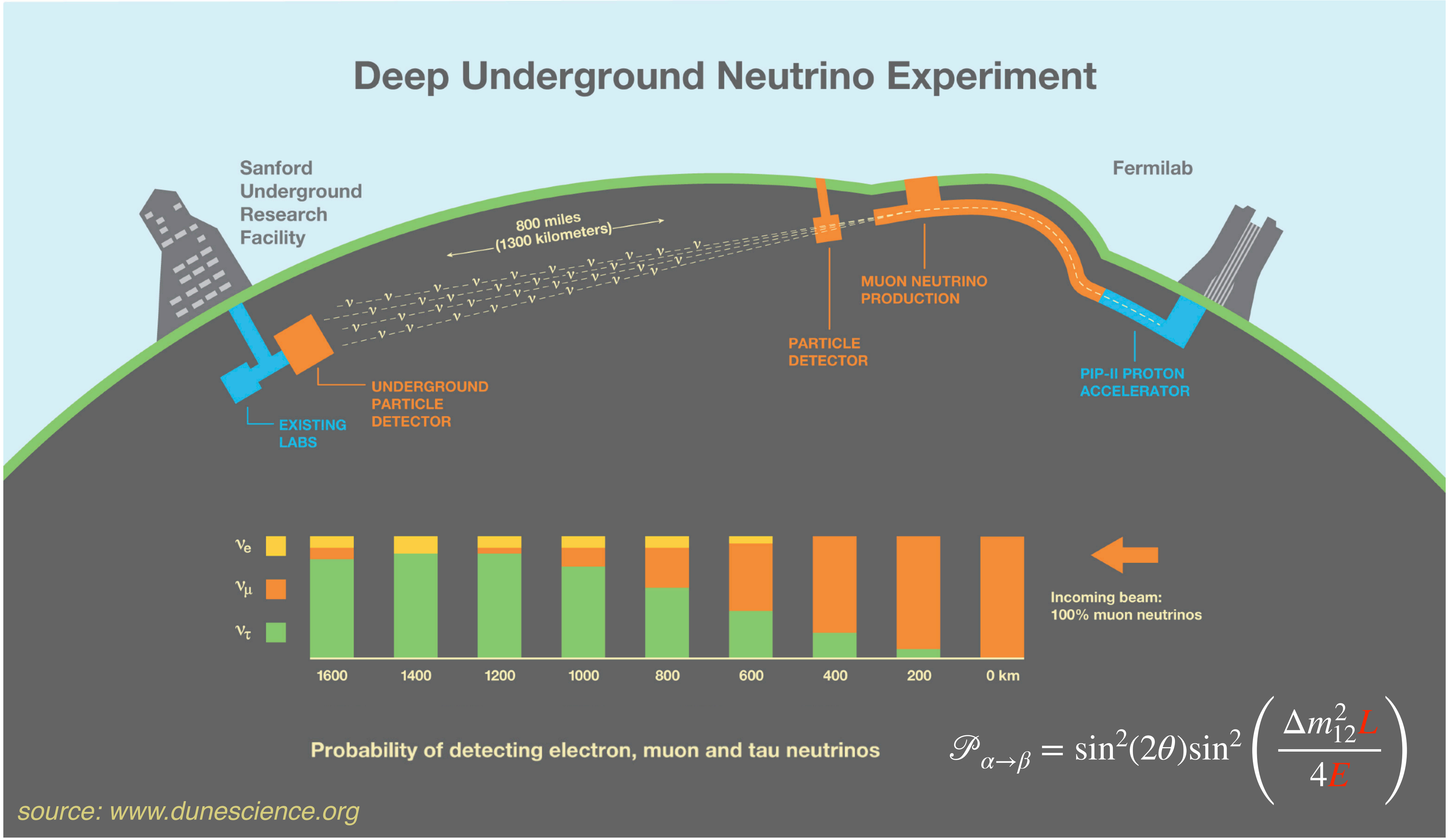


- Constraints on symmetry energy: S_0= 27 - 33 MeV L = 41 - 49 MeV

- N2LO$_{sat}$ well in agreement with experiment in mass range A= 40-48

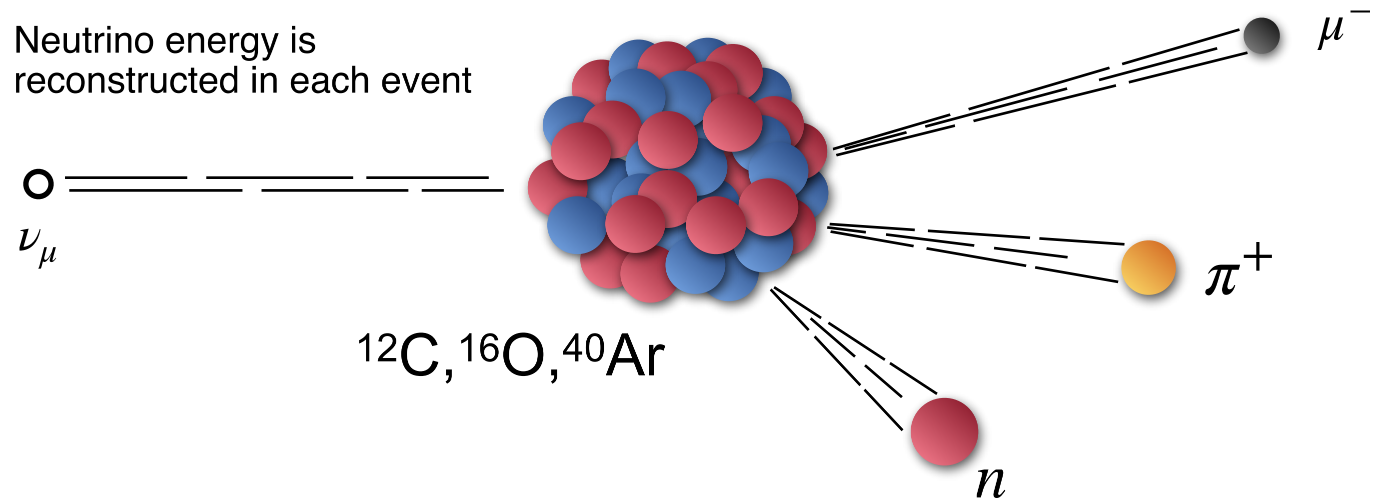
Lepton-nucleus scattering

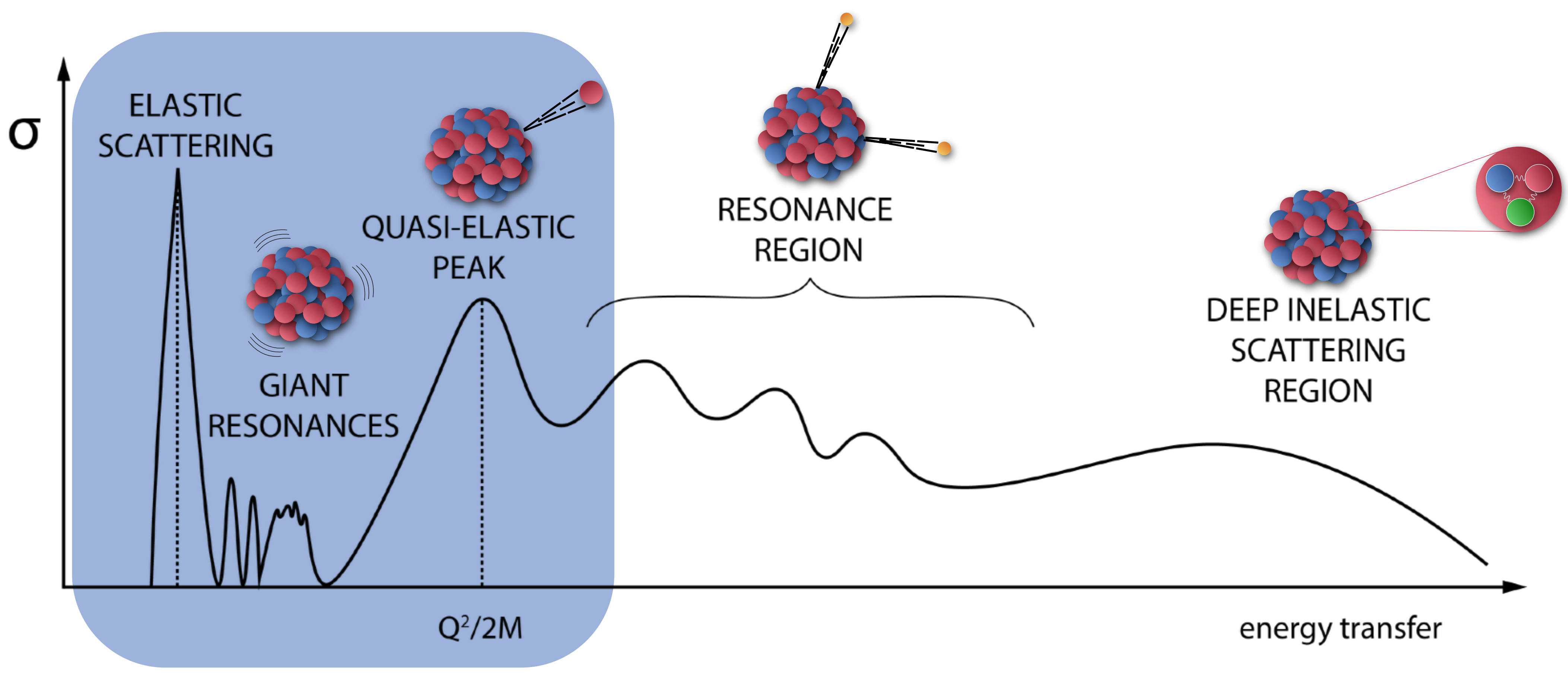
Neutrino Oscillations



$$\mathscr{P}_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{12} L}{4E}\right)$$

Aims and challenges





Electrons and neutrinos

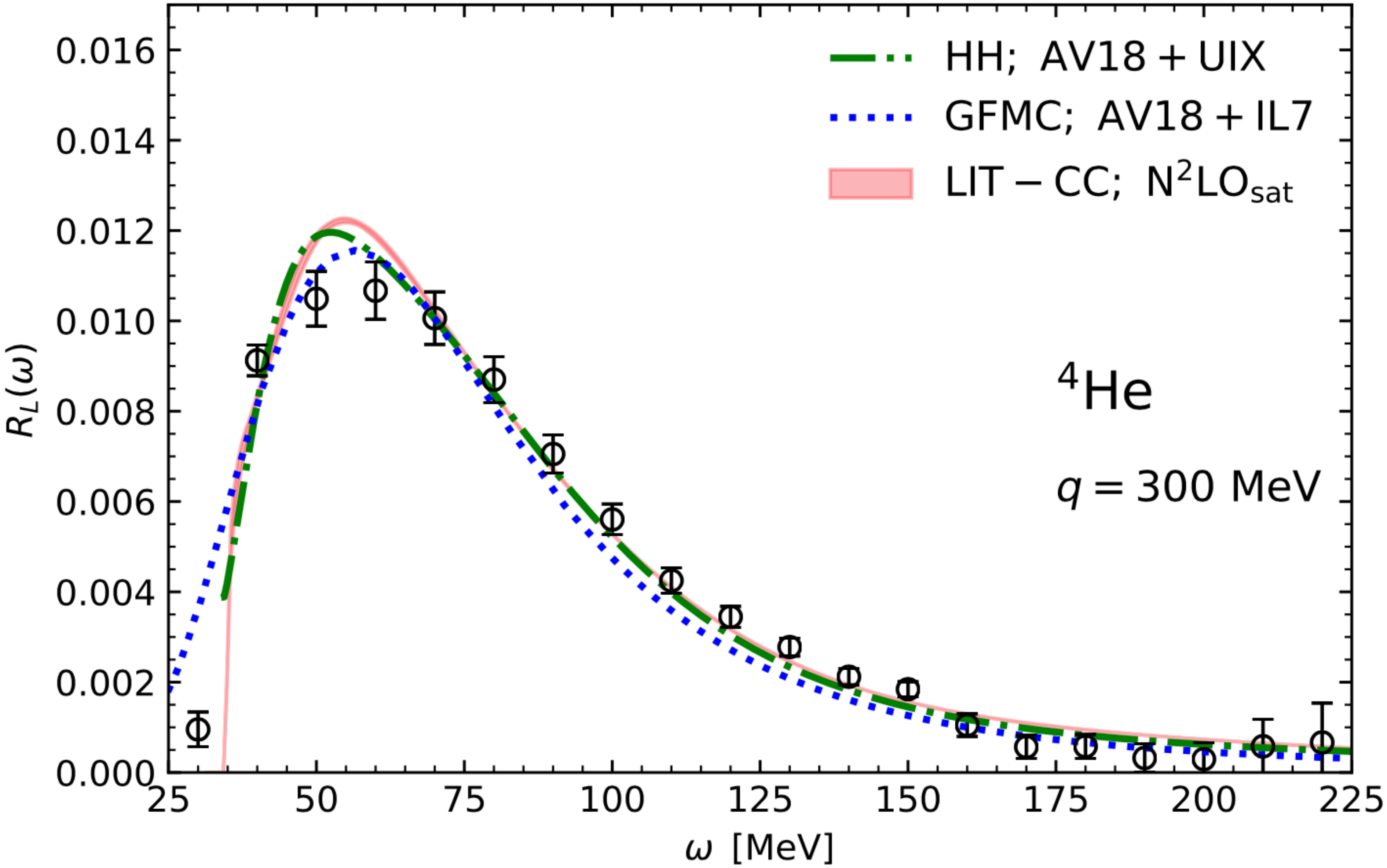
ν-A scattering $$\left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\,\mathrm{d}\omega}\right|_{\nu/\bar{\nu}} = \sigma_0\left[\ell_{CC}R_{CC} + \ell_{CL}R_{CL} + \ell_{LL}R_{LL} + \ell_{T}R_{T} \pm \ell_{T'}R_{T'}\right]$$

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

Recent Highlights on (e,e')

Benchmark for the ^{4}He nucleons

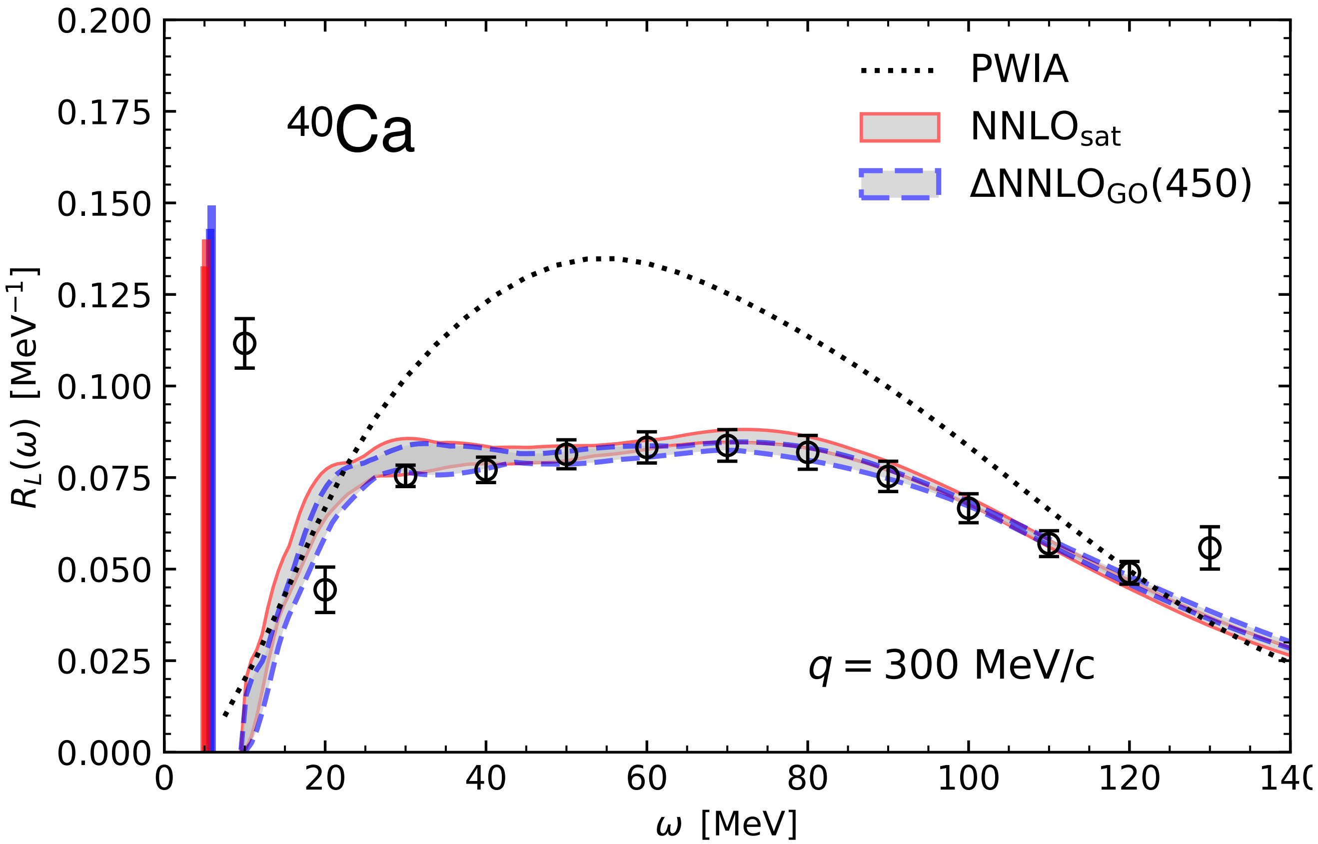
Sobczyk, Acharya, SB, Hagen, PRL **127** (2021) 7, 072501

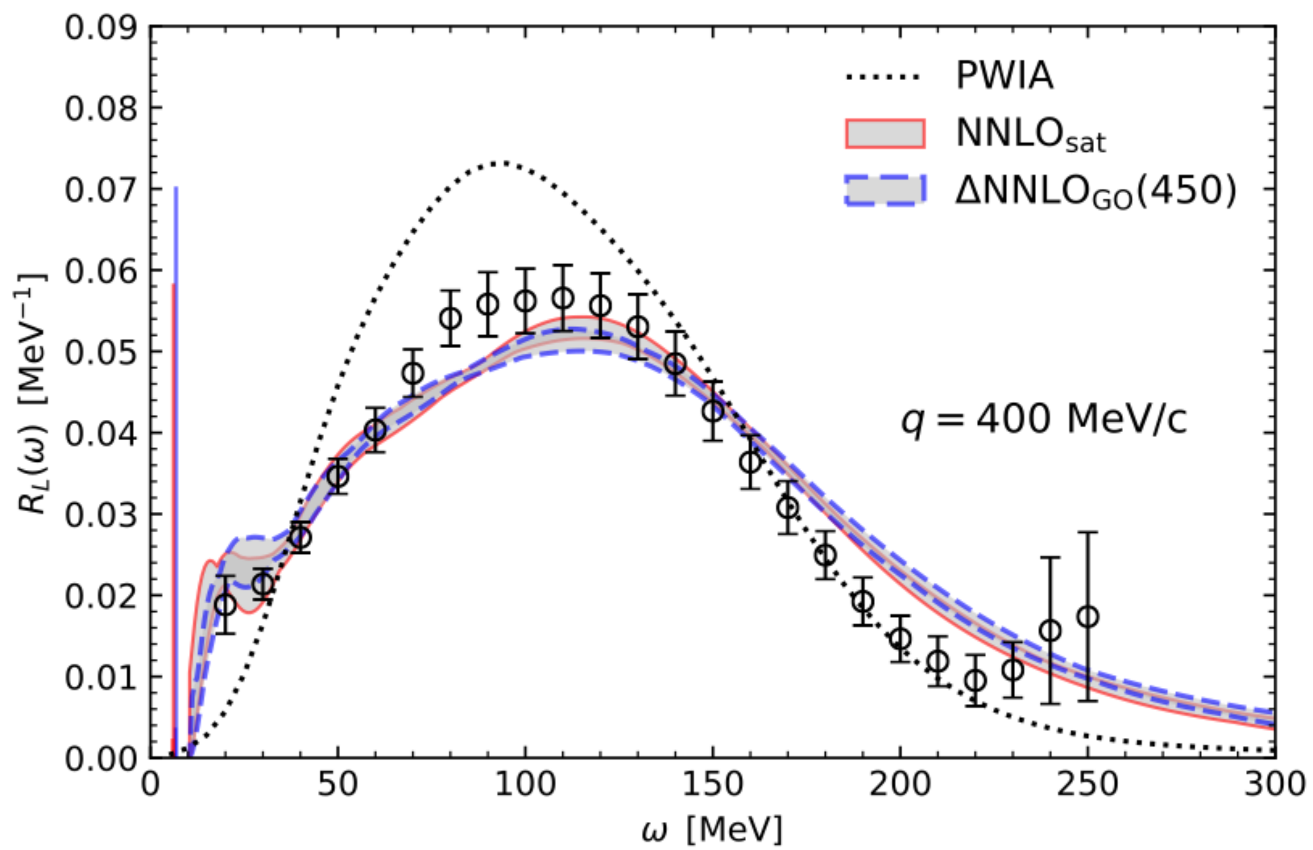


Recent Highlights on (e,e')

First ab-initio results for many-body system of 40 nucleons

Sobczyk, Acharya, SB, Hagen, PRL **127** (2021) 7, 072501

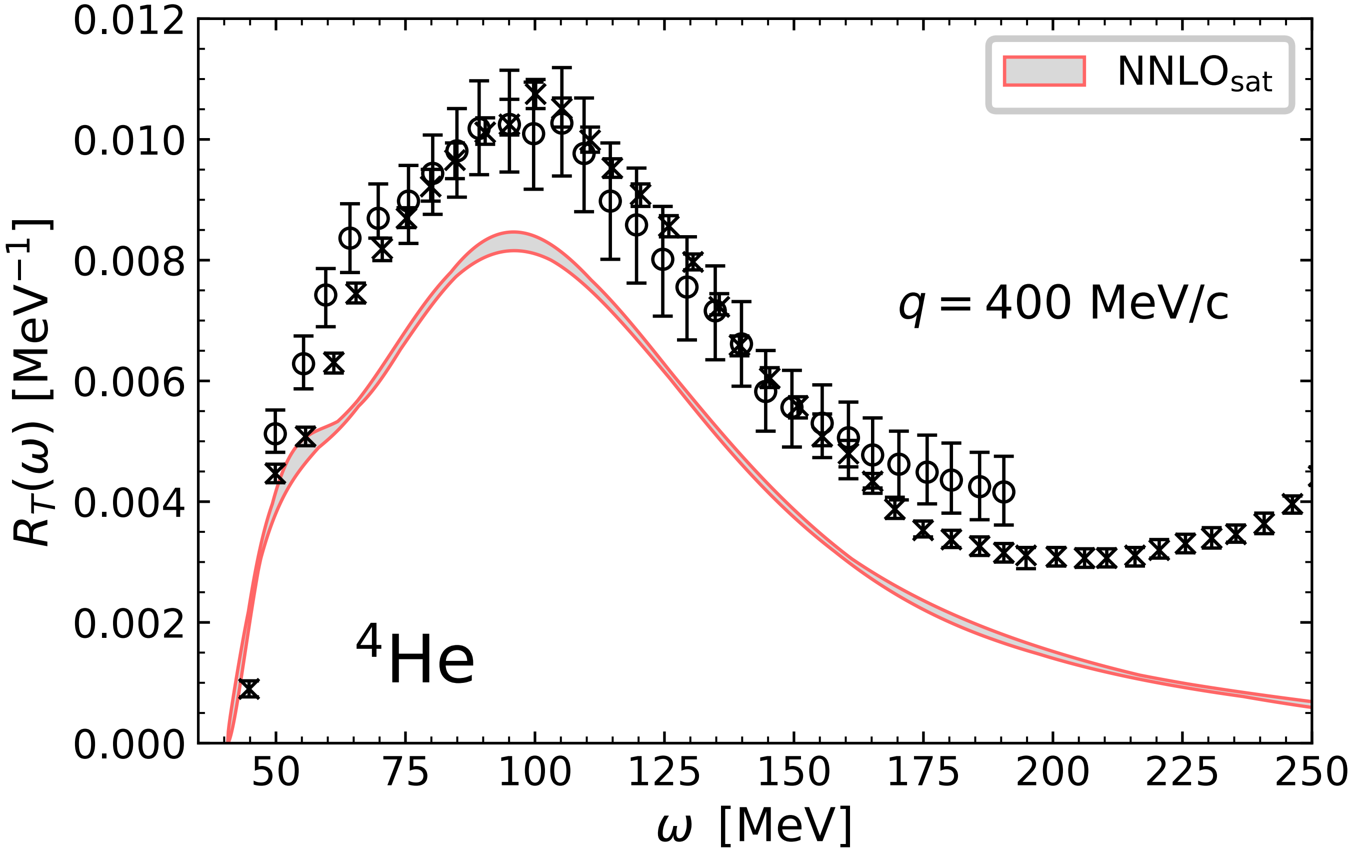


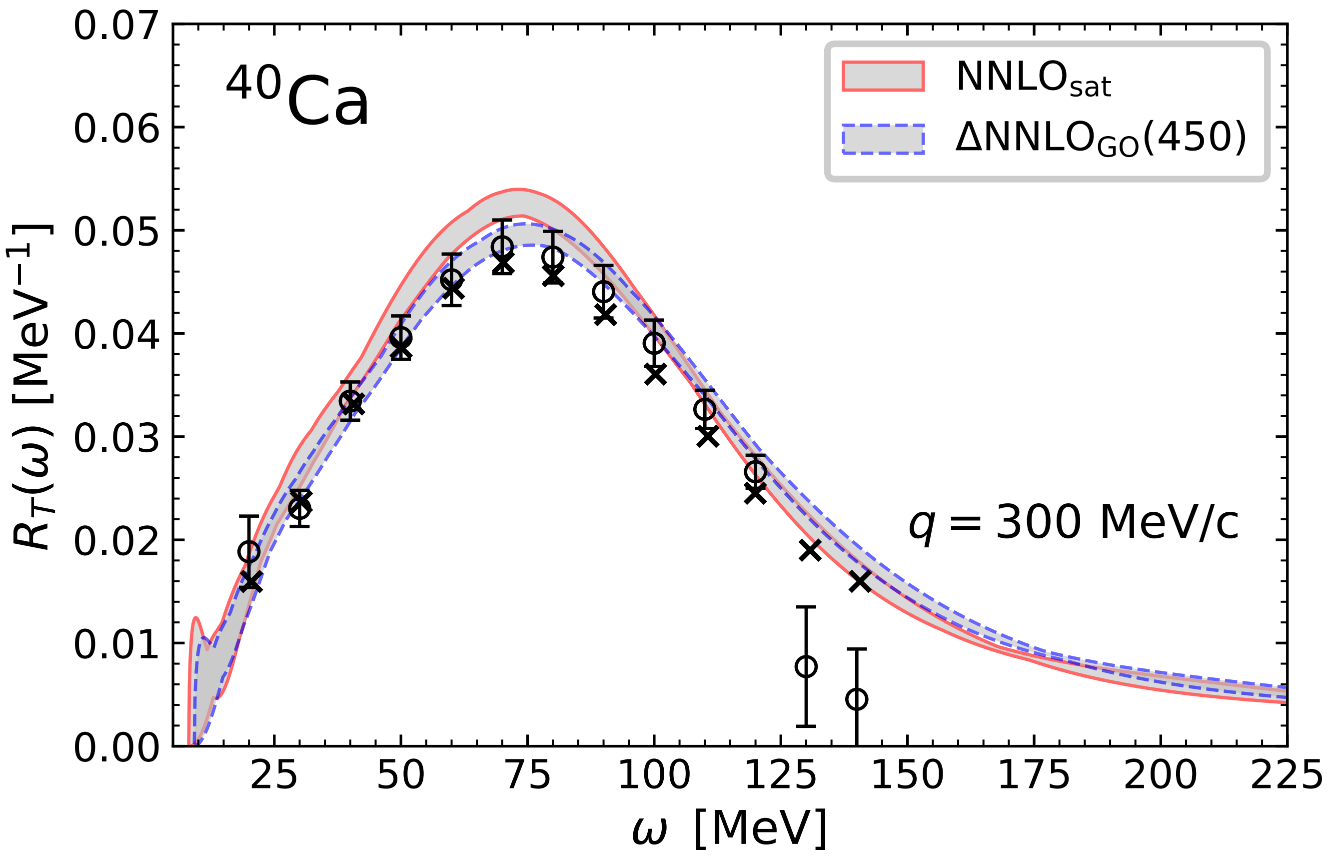


Recent Highlights on (e,e')

Transverse Response Functions

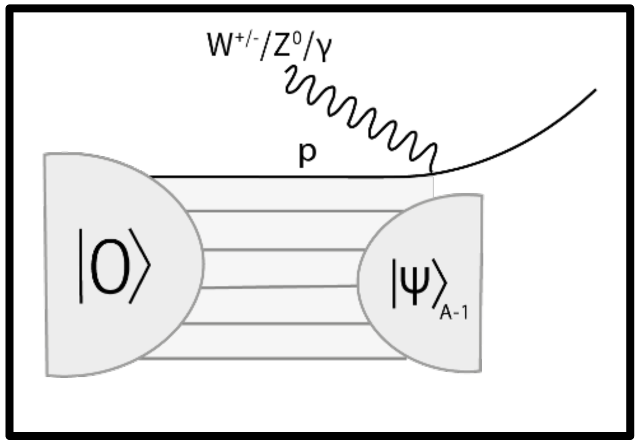
Acharya, Sobcyzk, SB, Hagen, in preparation



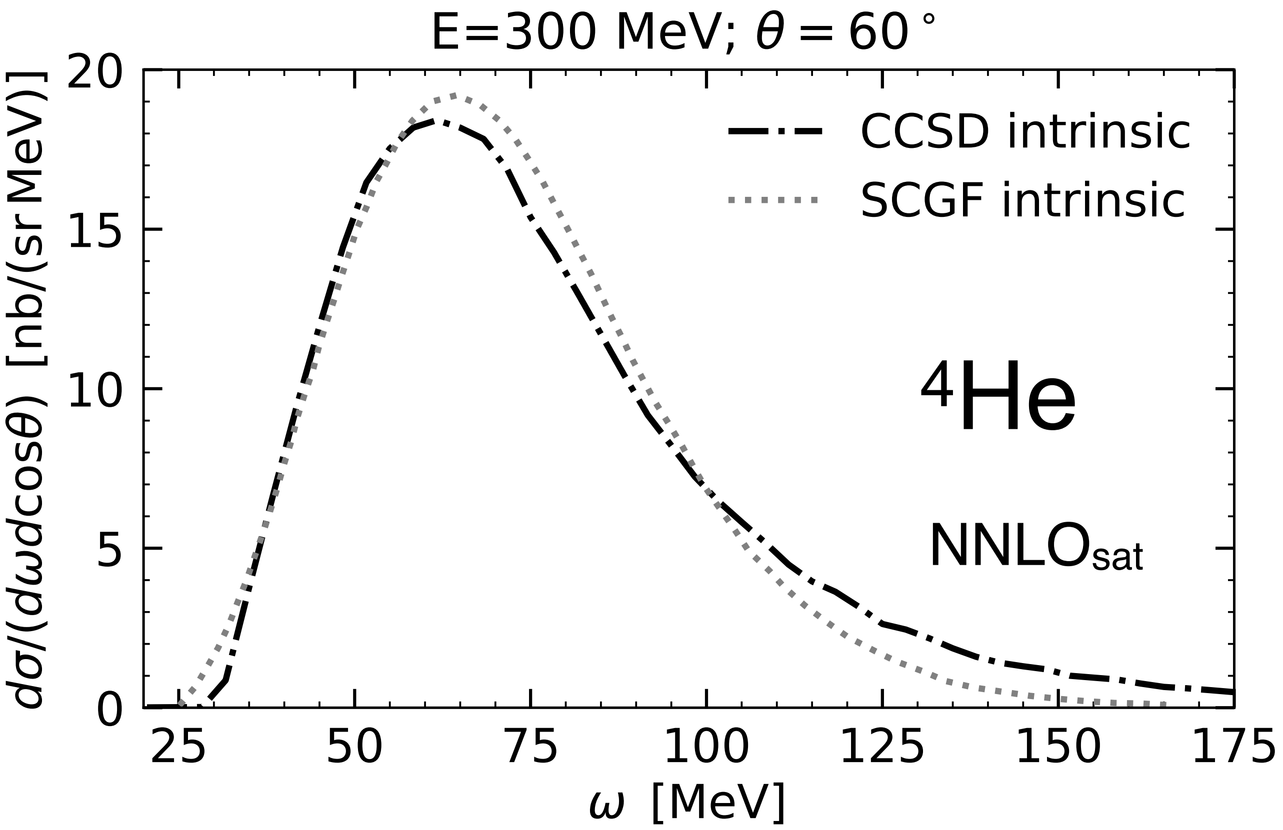


Recent Highlights on (e,e')

Access higher energies with Spectral Functions

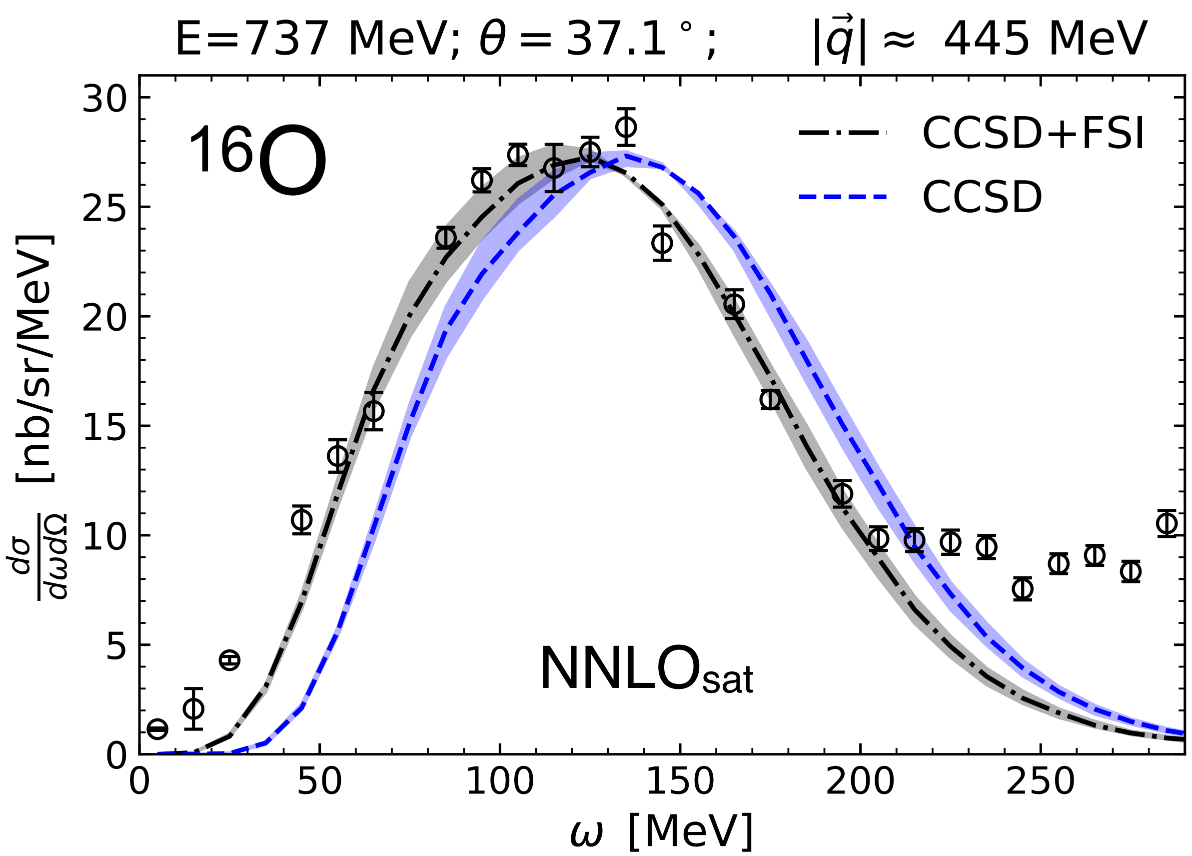


Sobcyzk, SB, Hagen, Papenbrock, Phys. Rev. C **106**, 034310 (2022)



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

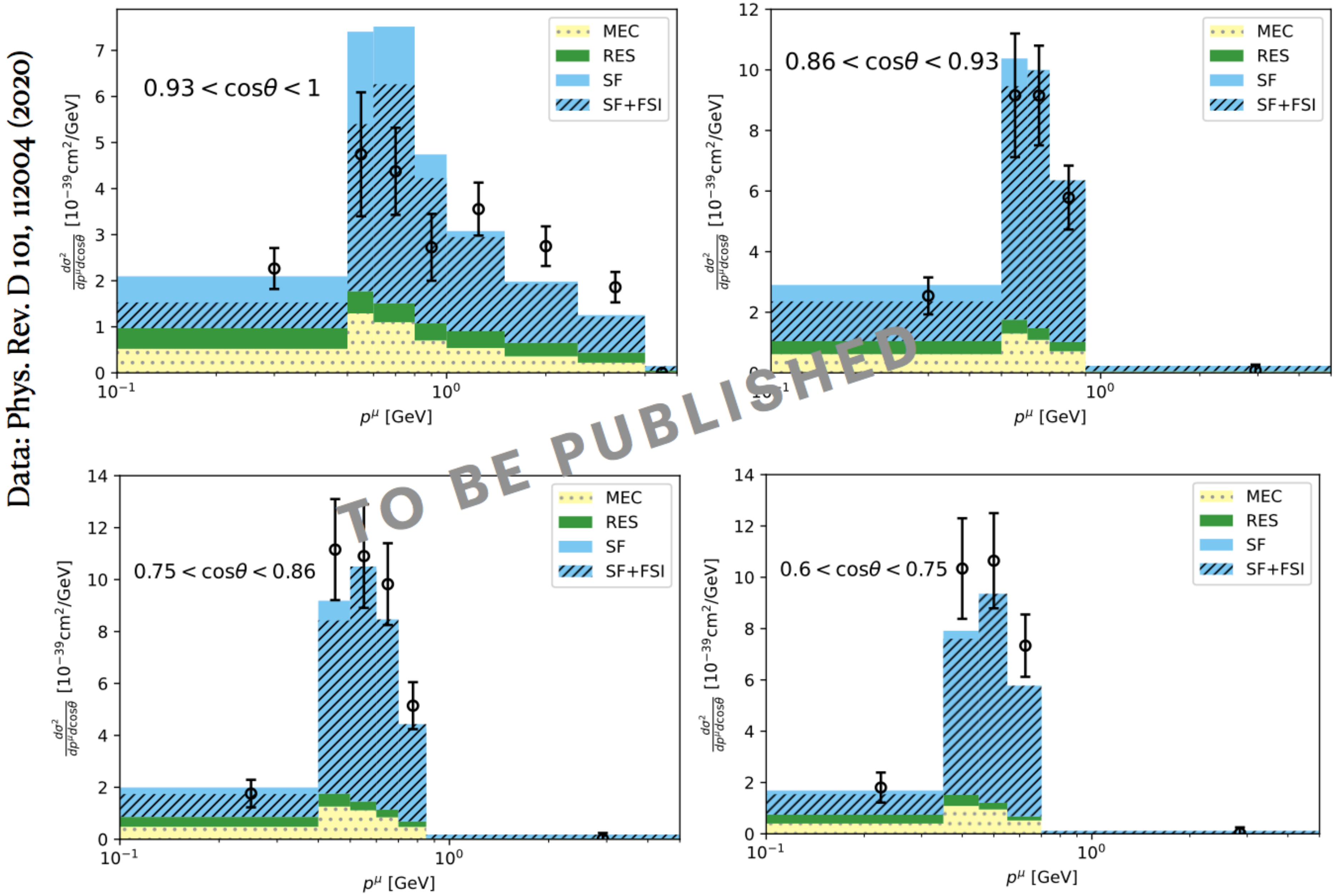
Sobcyzk, SB et al., to be submitted (2023)



Spectral functions for neutrinos

Sobcyzk, SB et al., to be submitted (2023)   T2K, CC0π, NuWro

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



Outlook

Substantial progress in first principle calculations of electroweak reactions

Thanks to all my collaborators:

B. Acharya, F. Bonaiti, W. Jiang, G. Hagen, T. Papenbrock, A. Schwenk,
J. Simonis, **J.E. Sobczyk,** et al.

Thanks for your attention!

25th European Conference on Few-Body Problems in Physics

25 EFB

Mainz, 30 July - 4 Aug, 2023

Topics:

- Hadron physics
- Nuclei and hypernuclei
- Electroweak processes
- Nuclear astrophysics
- Cold atoms and quantum gases
- Atoms and molecules
- Few-body methods
- Few-body aspects of many-body systems