Electroweak Processes from First Principles

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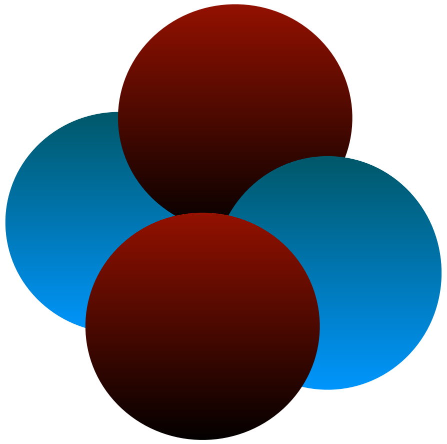
SFB1245 Annual Workshop

Ab initio nuclear theory



- Start from neutrons and protons as building blocks (centre of mass coordinates, spins, isospins)

- Solve the non-relativistic quantum mechanical problem of A-interacting nucleons

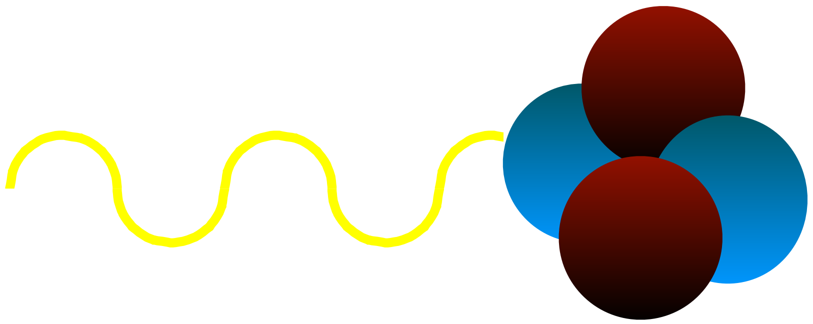
$$H|\psi_i\rangle = E_i|\psi_i\rangle$$

$$H = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + \dots$$

using interactions from chiral effective field theory

- Find numerical solutions with no approximations or controllable approximations

Coupling to the electroweak field



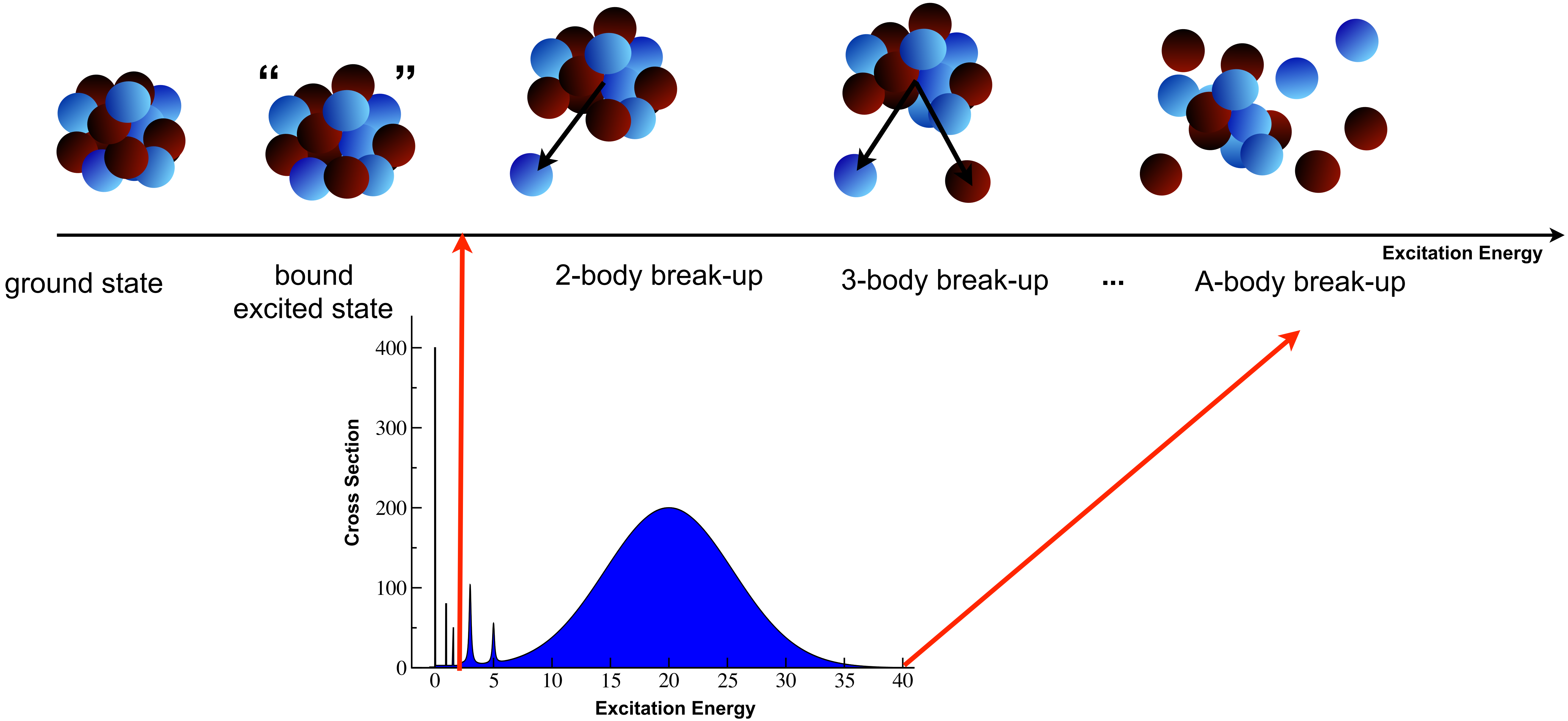
Cross Section $\sigma_{ew} \sim R(\omega) = \sum\!\!\!\!\!\!\int_f \left| \left\langle \psi_f \middle| \Theta \middle| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$

Electroweak operator

The continuum problem

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

Depending on E_f, many channels may be involved



Integral Transforms

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

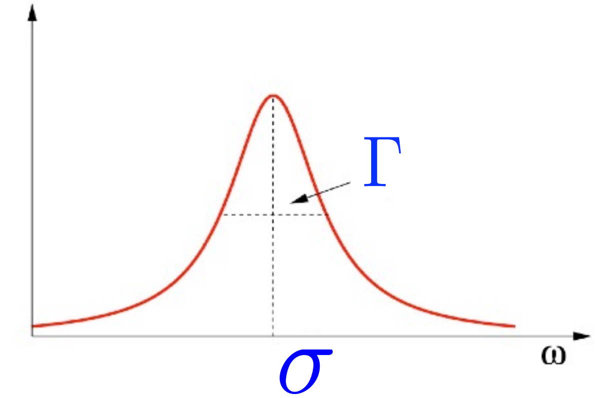
Exact knowledge limited in energy and mass number

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

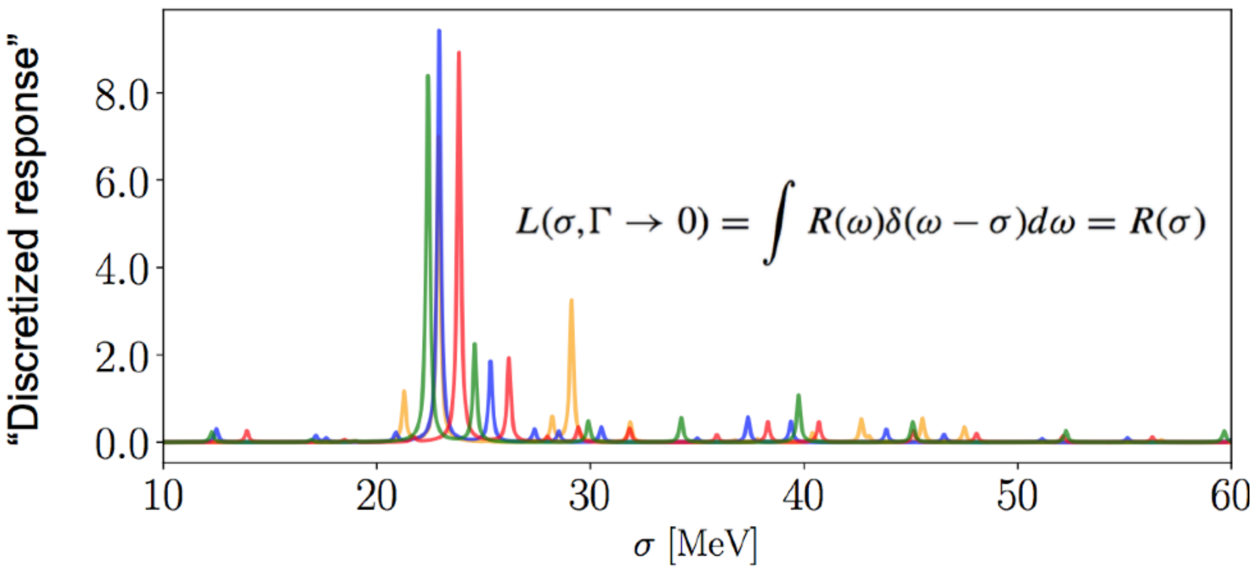
Sum Rules

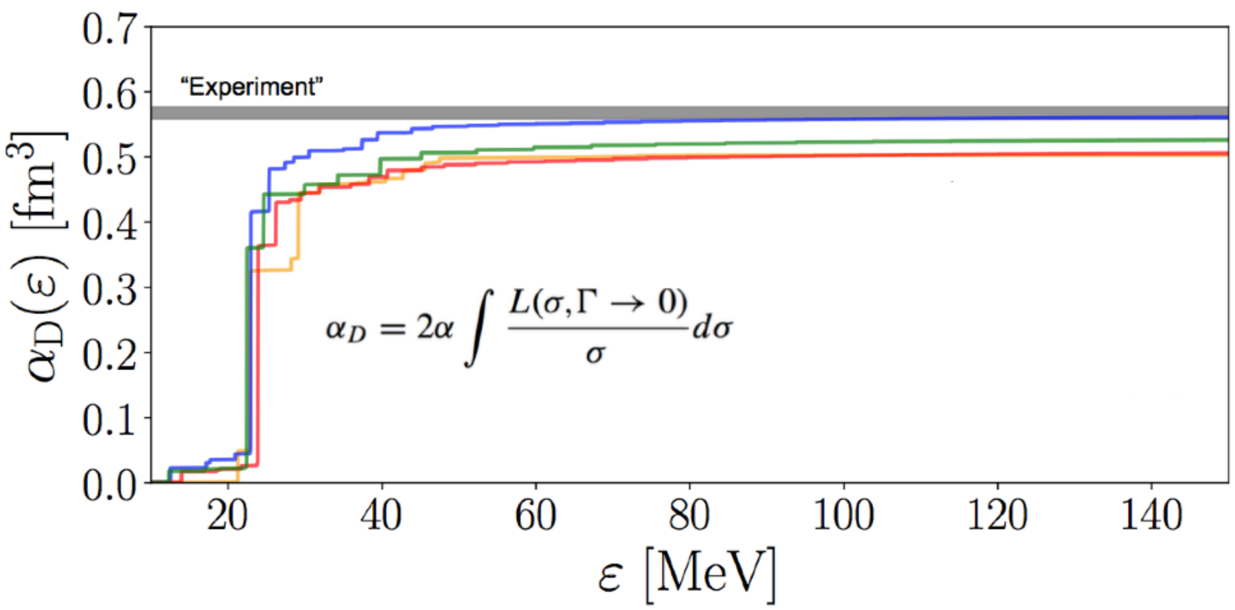
$$m_n = \int_0^\infty d\omega\ \omega^n R(\omega) = \langle \Psi_0 | \hat{\Theta}^\dagger (\hat{H} - E_0)^n \hat{\Theta} | \Psi_0 \rangle$$

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 $\Gamma \to 0$

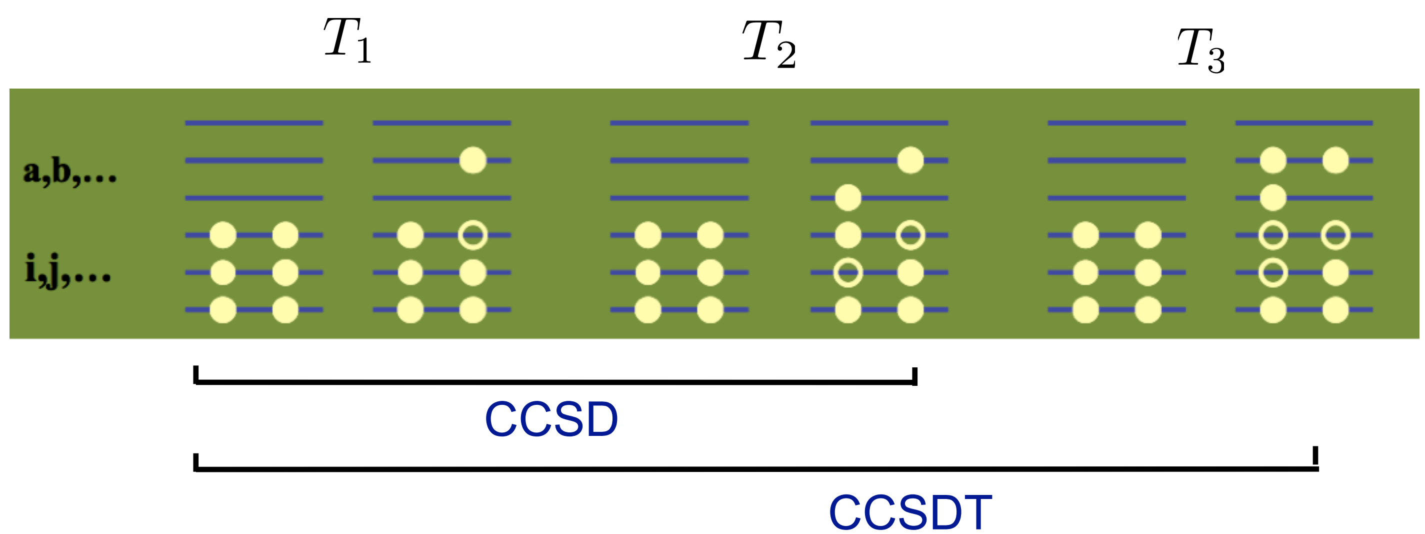




Coupled-cluster theory formulation

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

cluster expansion



See also
F. Bonaiti's talk

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

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

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

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

Electric Dipole Polarizability (SFB 1245, B04)

Motivation for B04

See Xavier Roca-Maza's talk

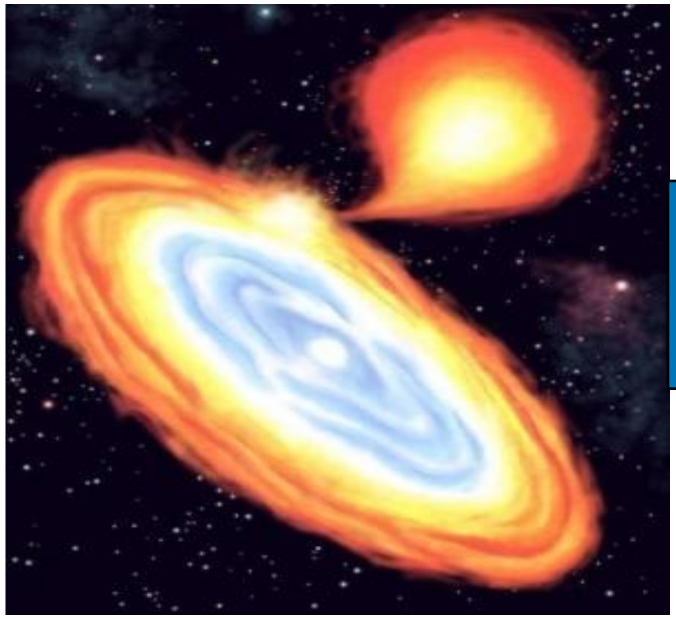
$$E(\rho,\delta) = E(\rho,0) + S(\rho)\delta^2 + \mathcal{O}(\delta^4)$$

$$\rho = \rho_n + \rho_p, \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

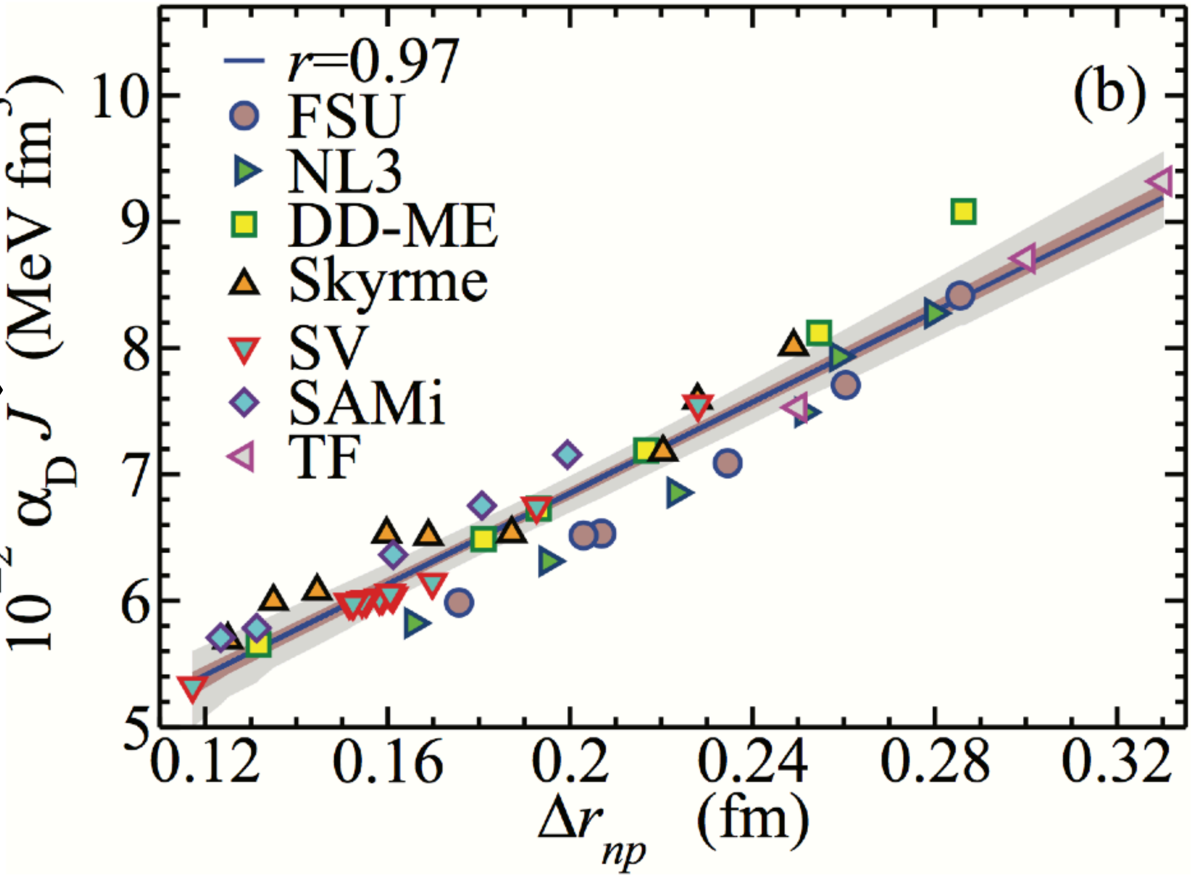
$$S(\rho) = S_0 + \frac{L}{3\rho_0}(\rho - \rho_0) + \frac{K_{sym}}{18\rho_0^2}(\rho - \rho_0)^2 + \dots$$

Symmetry energy at saturation density

Slope parameter, related to pressure of pure neutron matter at saturation density

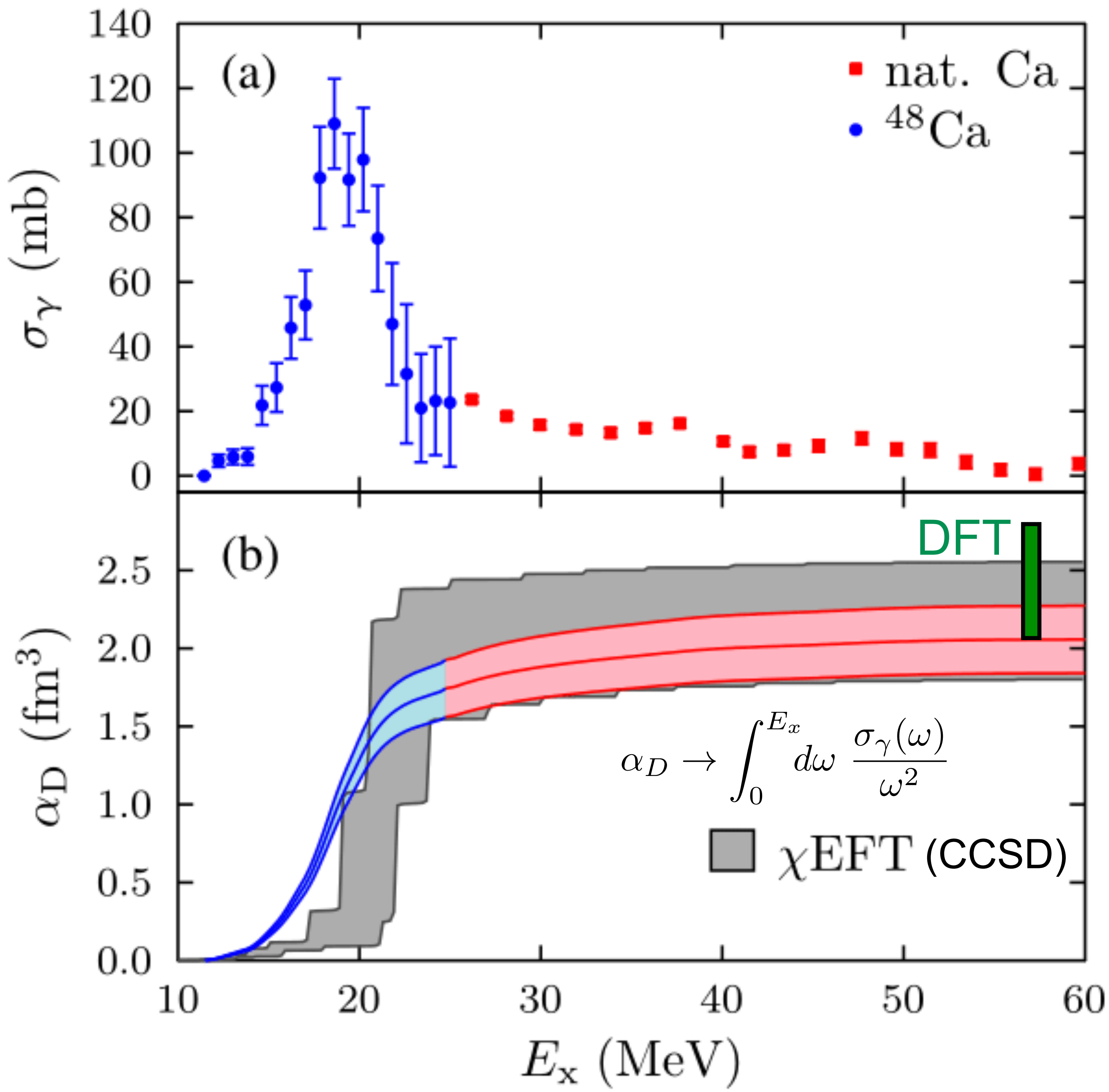


Laboratory measurements on finite nuclei are crucial

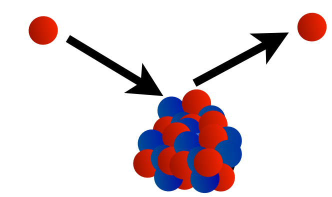


The ^{48}Ca nucleus

Birkhan, Miorelli, SB *et al.*, Phys. Rev. Lett. **118,** 252501 (2017)



RCPN (p,p') experiment



New constraint on the EOS

$$28.5 \leq S_0 \leq 33.3 \quad \text{MeV}$$
$$43.8 \leq L \leq 48.6 \quad \text{MeV}$$

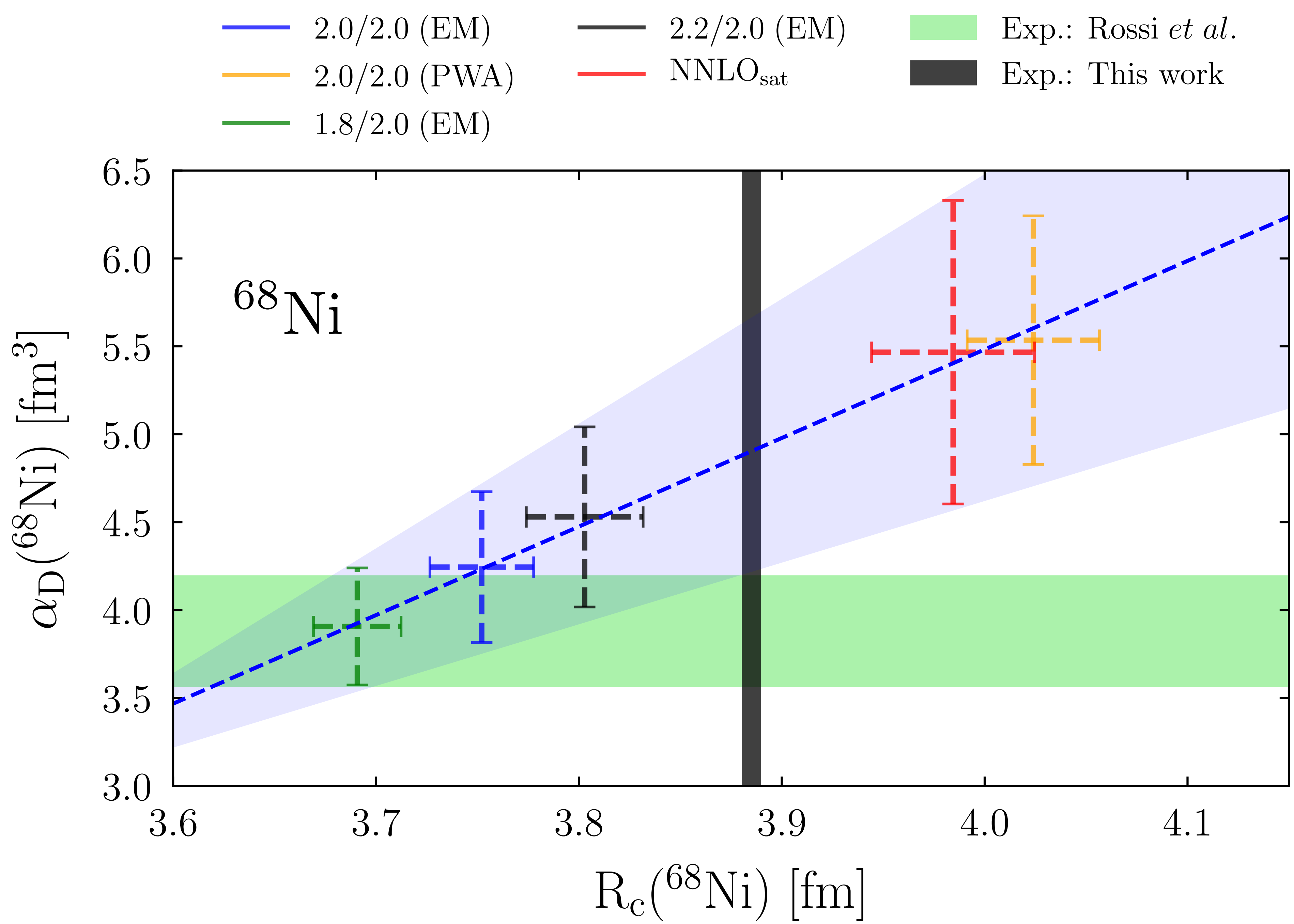
Improved correlations: CCSD-T1

Miorelli, SB et al., PRC **98**, 014324 (2018)

Simonis, SB, Hagen, EPJA **55**, 241 (2019)

The ^{68}Ni nucleus

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



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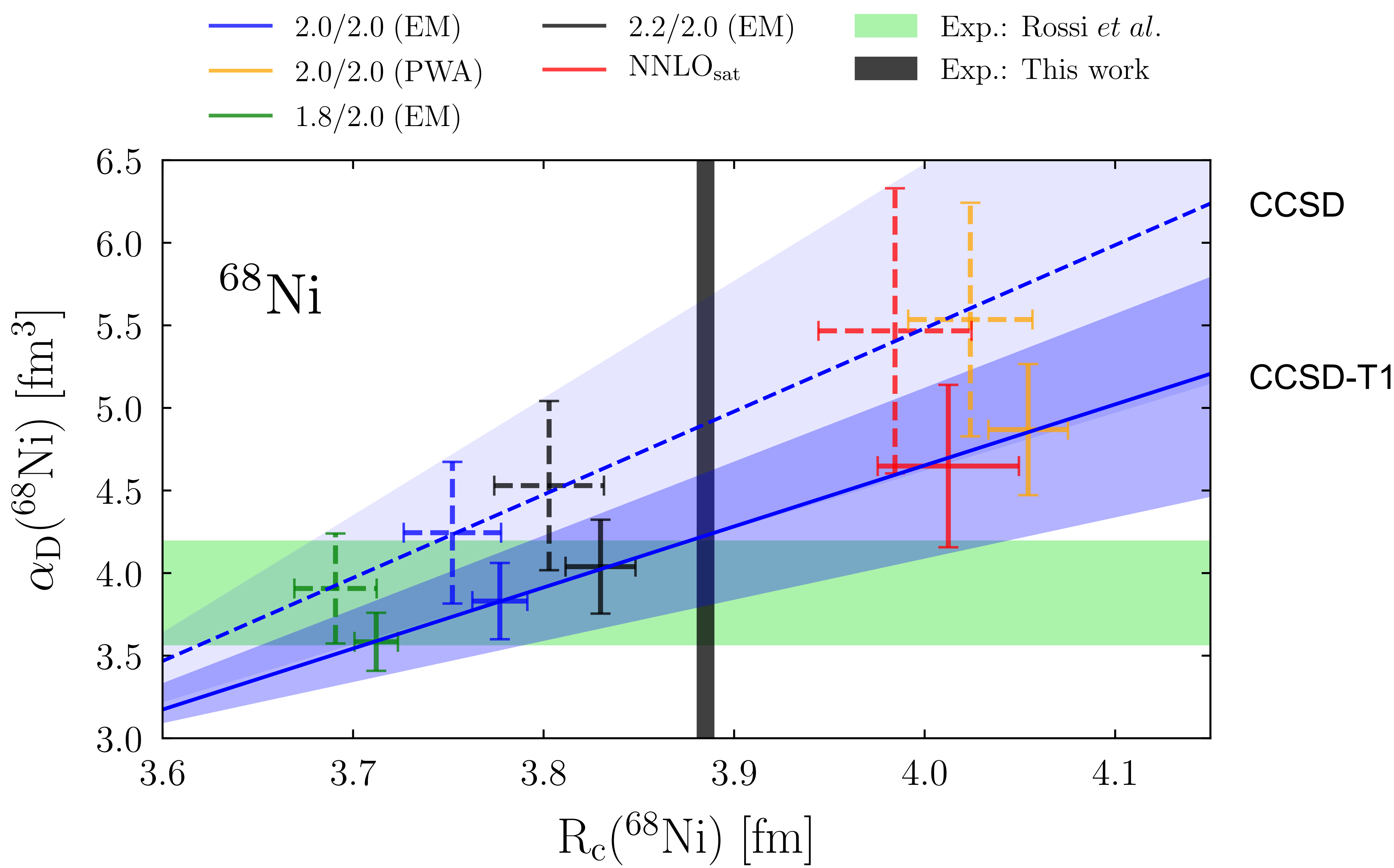
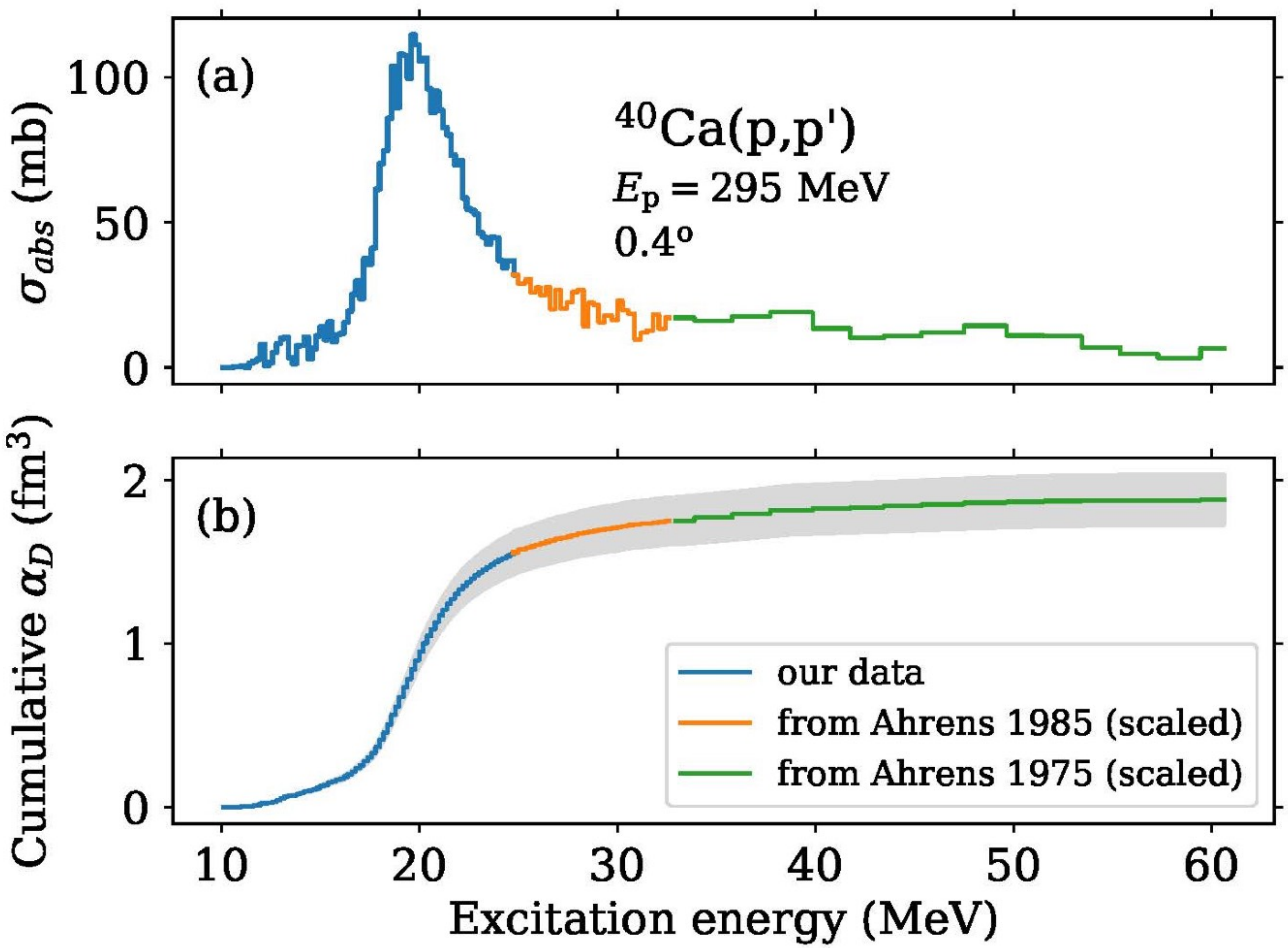
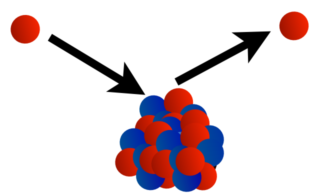
S.Kaufmann, J. Simonis, SB *et al.*, PRL **104** (2020) 132505



R.W. Fearick et al, in preparation



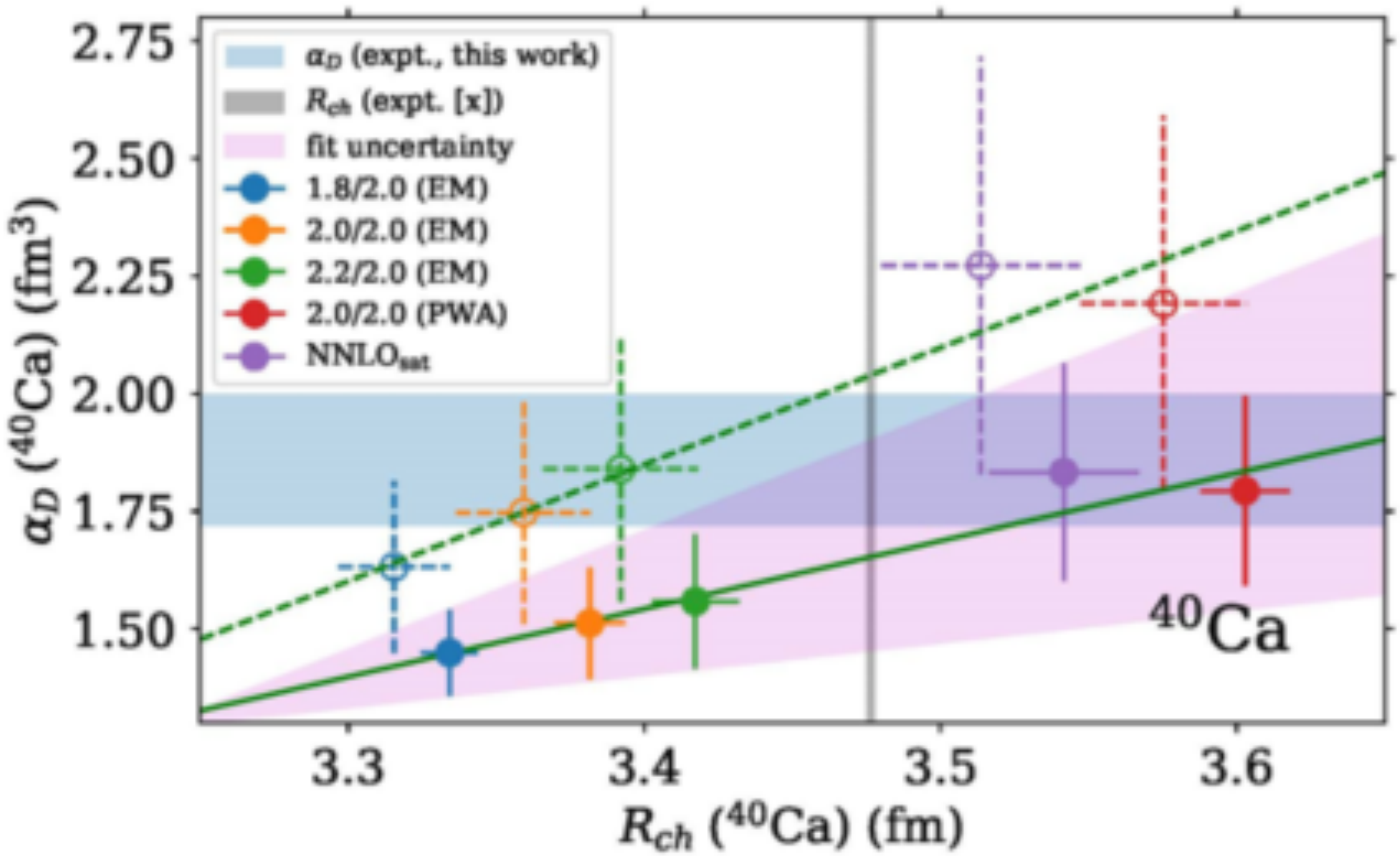
RCNP (p,p') scattering



α_D = 1.86(14) fm^3

The ^{40}Ca nucleus

R.W. Fearick et al, in preparation

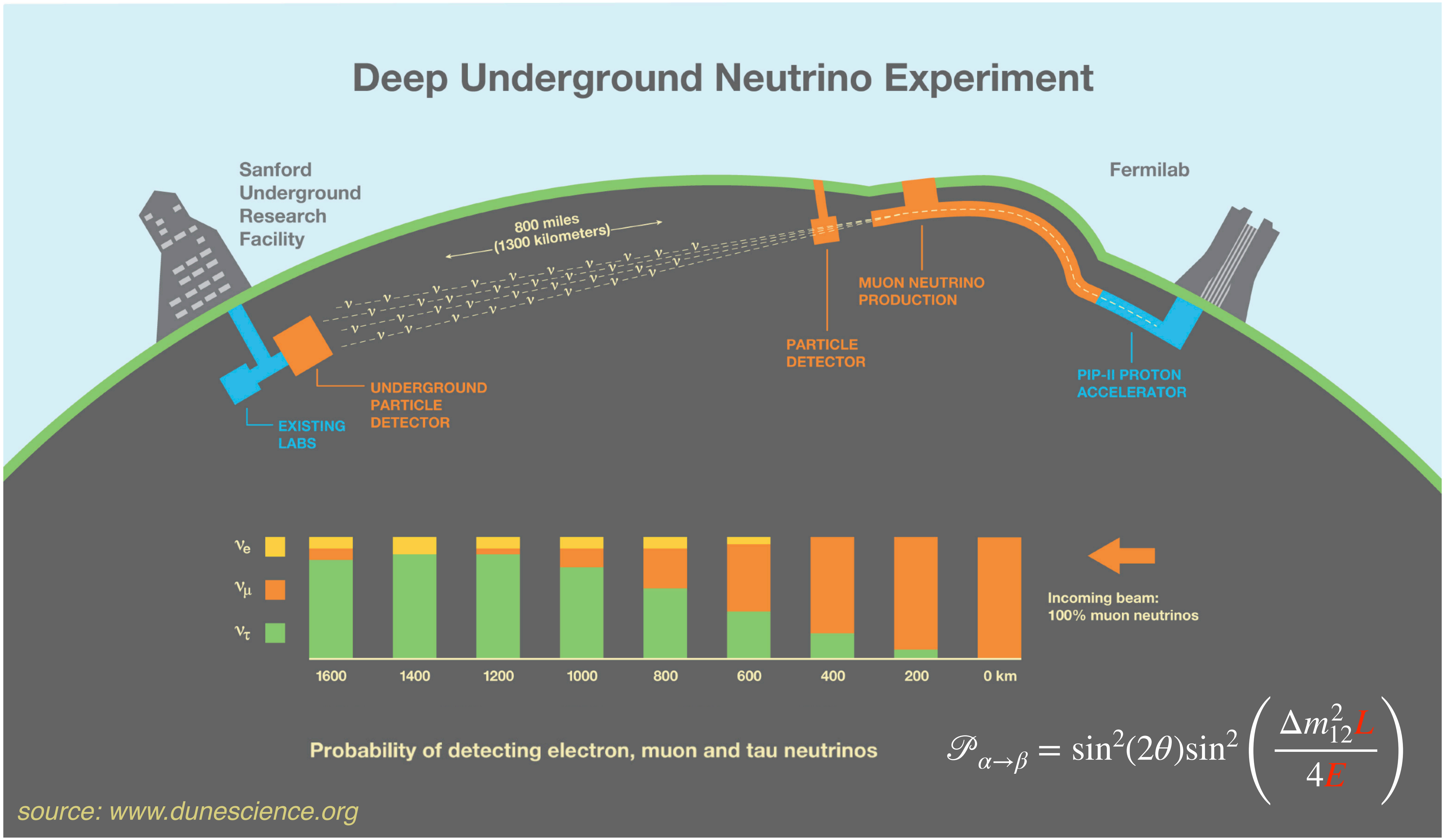


- Improved calculations with triple correlations in the ground state
- Constraints on symmetry energy: S_0= 28 - 32 MeV L = 41 - 49 MeV

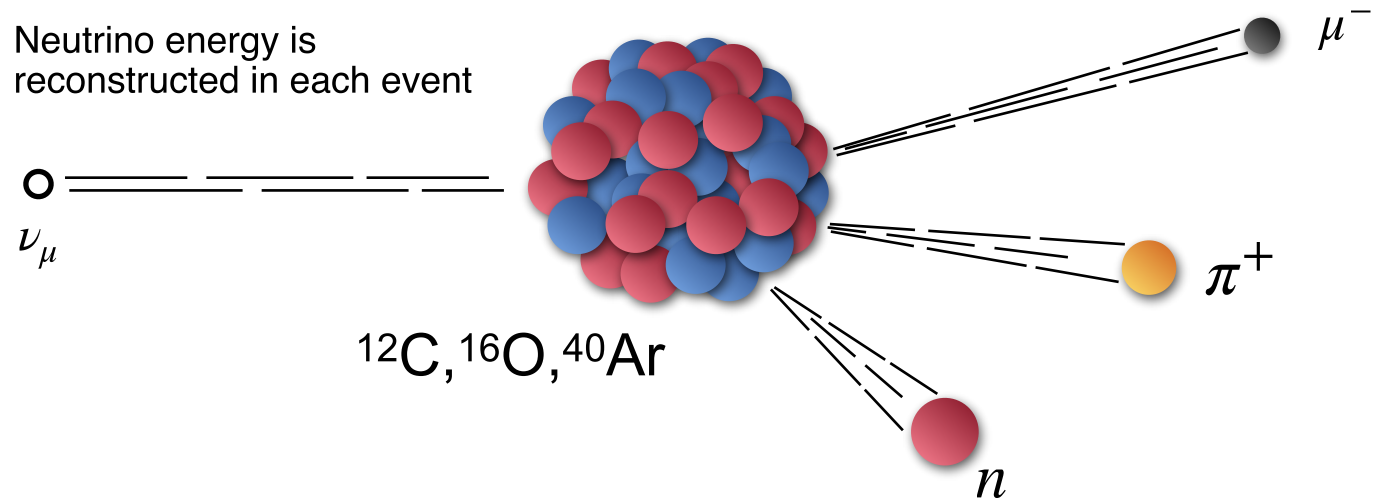
Title Text

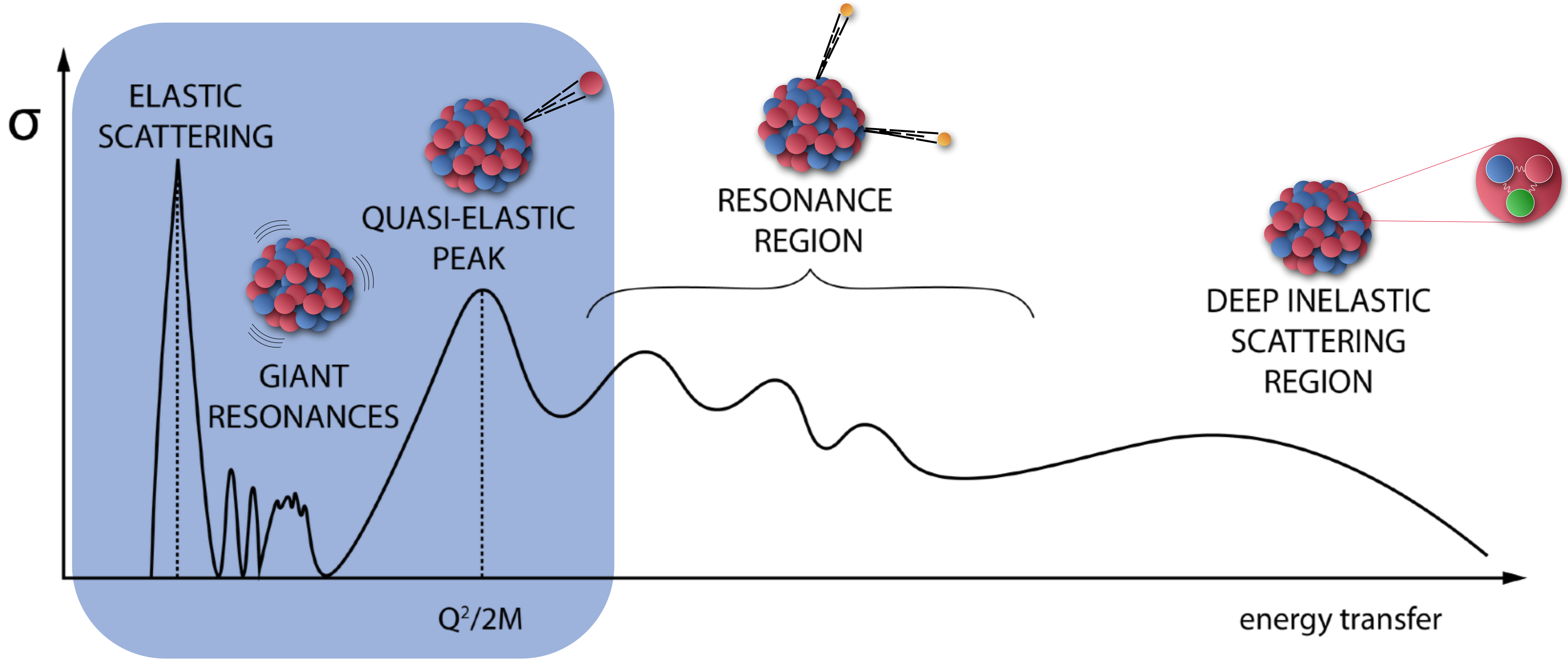
Applications to lepton-nucleus scattering

Neutrino Oscillations



Aims and challenges





Electrons and neutrinos

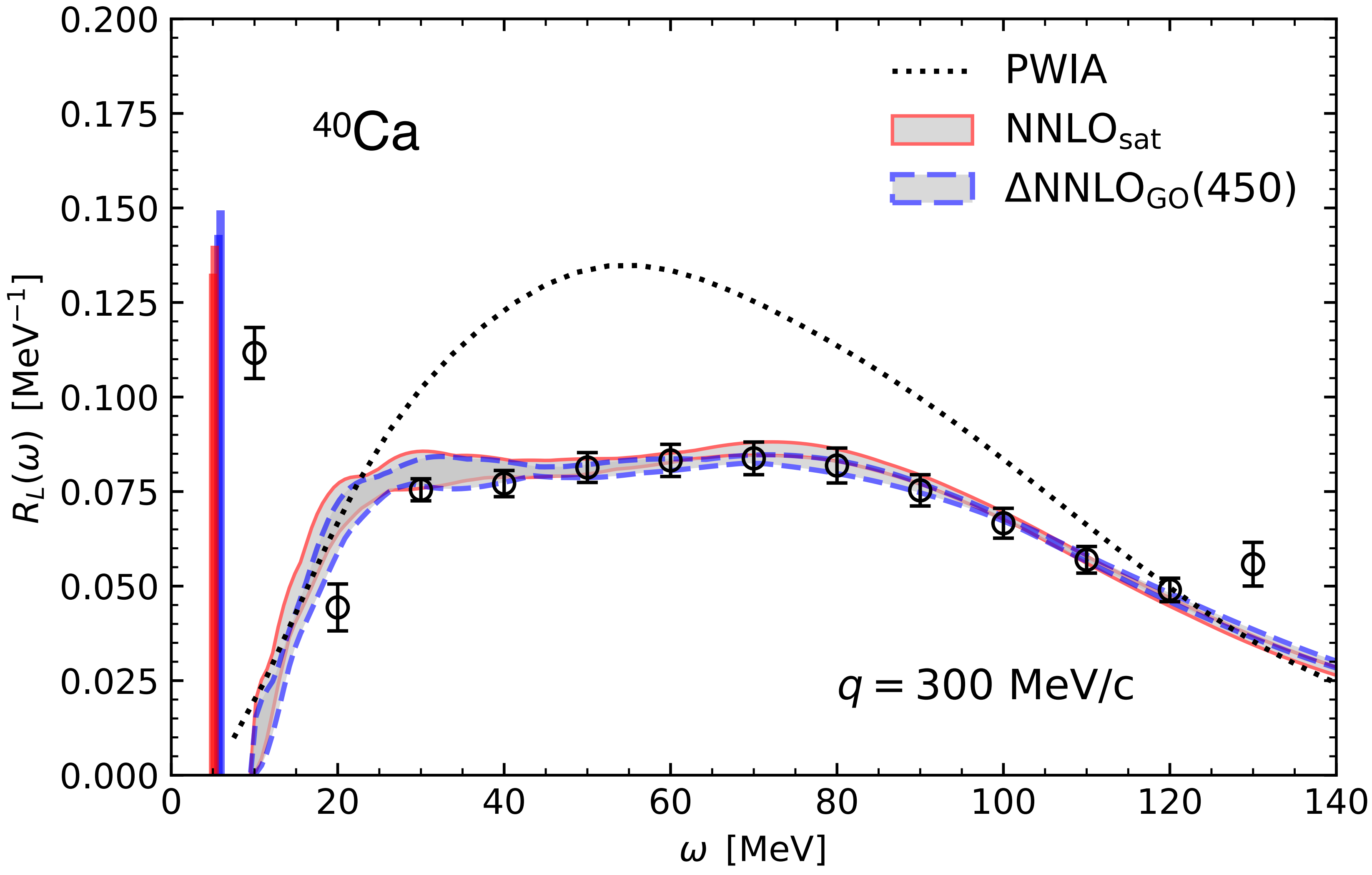
ν-A scattering $$\left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\,\mathrm{d}\omega}\right|_{\nu/\bar{\nu}} = \sigma_0\left[\ell_{CC}R_{CC} + \ell_{CL}R_{CL} + \ell_{LL}R_{LL} + \ell_T R_T \pm \ell_{T'}R_{T'}\right]$$

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')

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

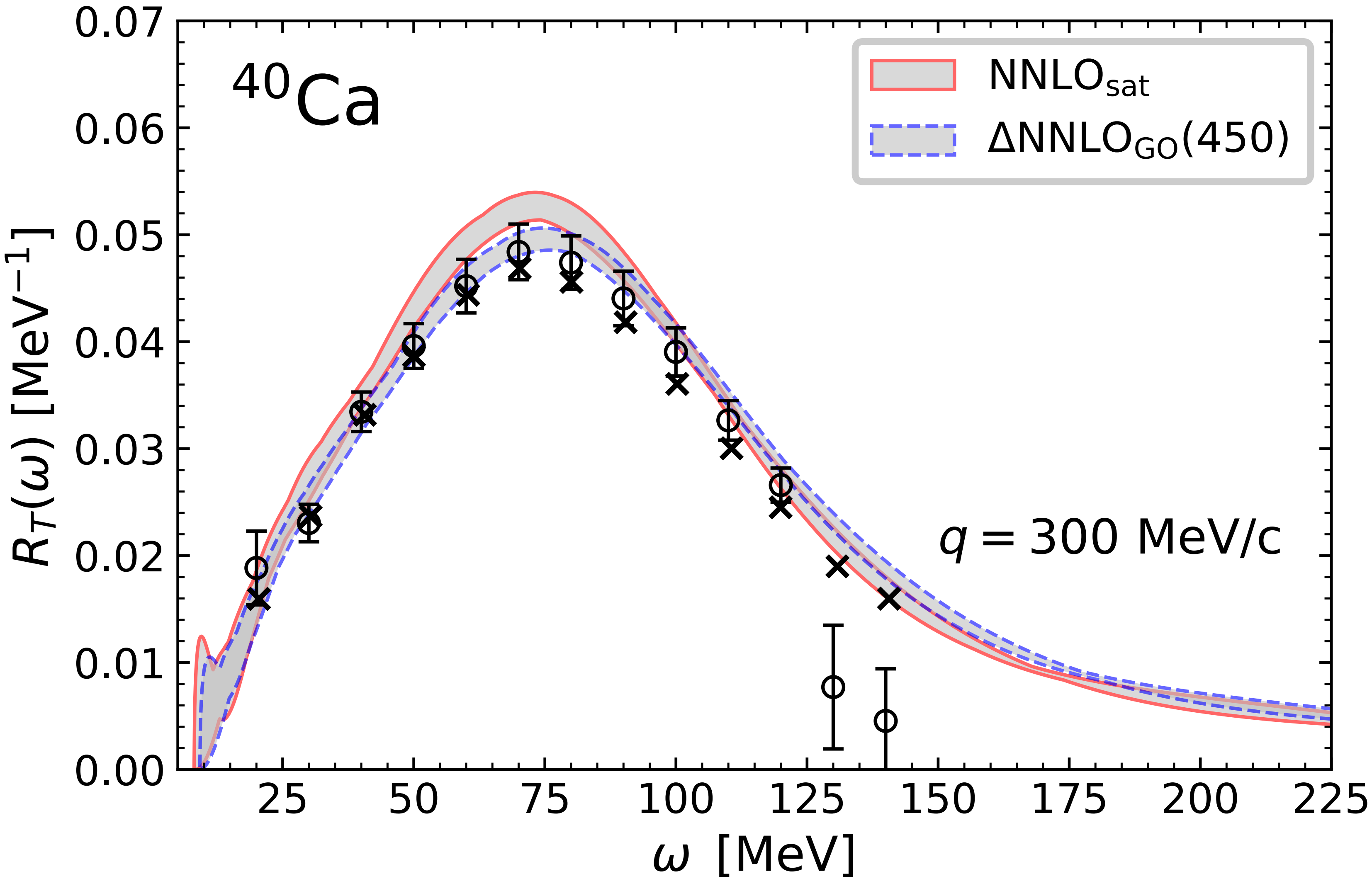
Sobcyzk, Acharya, SB, Hagen, PRL **127** (2021) 7, 072501



Recent Highlights on (e,e')

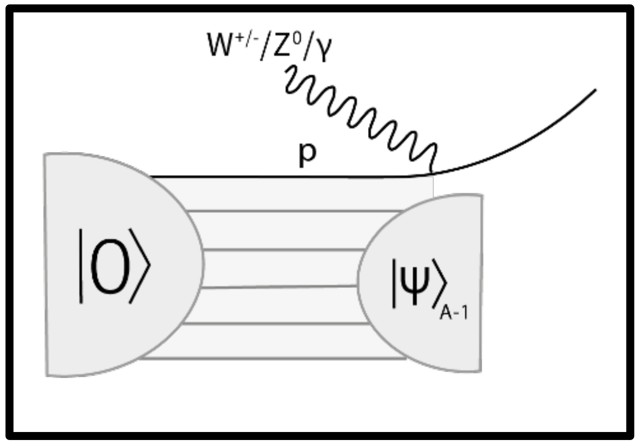
Inelastic transverse response function

Acharya, Sobcyzk, SB, Hagen, in preparation

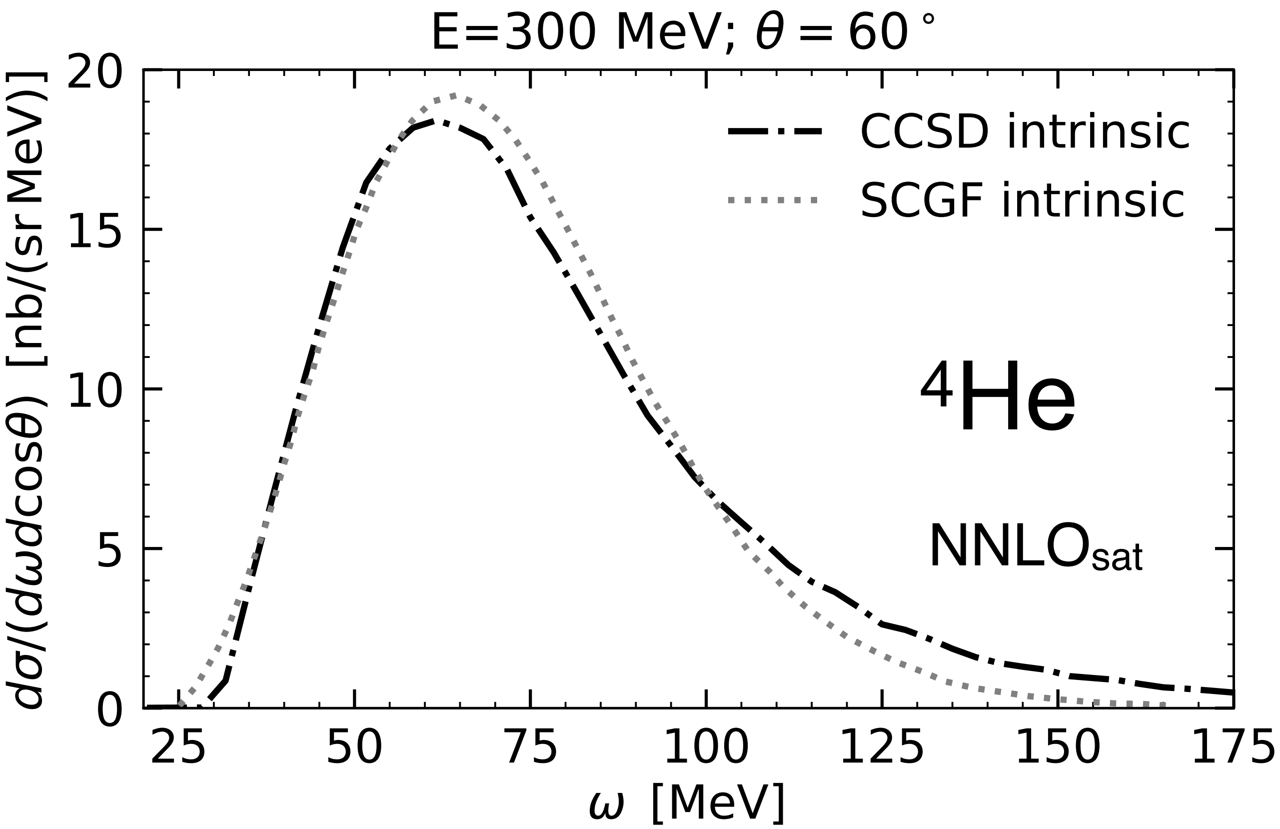


Recent Highlights on (e,e')

Access higher energies with Spectral Functions

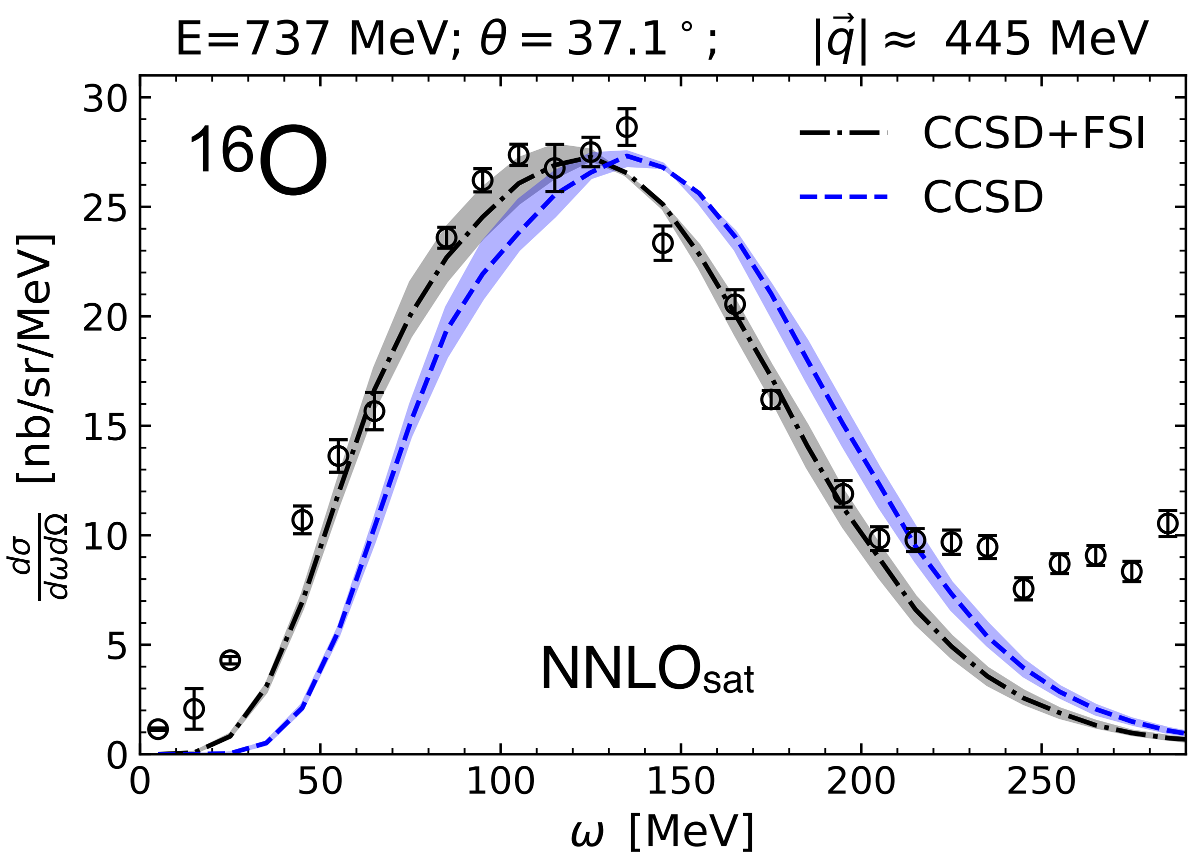


Sobcyzk, SB, Hagen, Papenbrock, Phys. Rev. C **106**, 034310 (2022)



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

Sobcyzk, SB et al., to be submitted (2022)



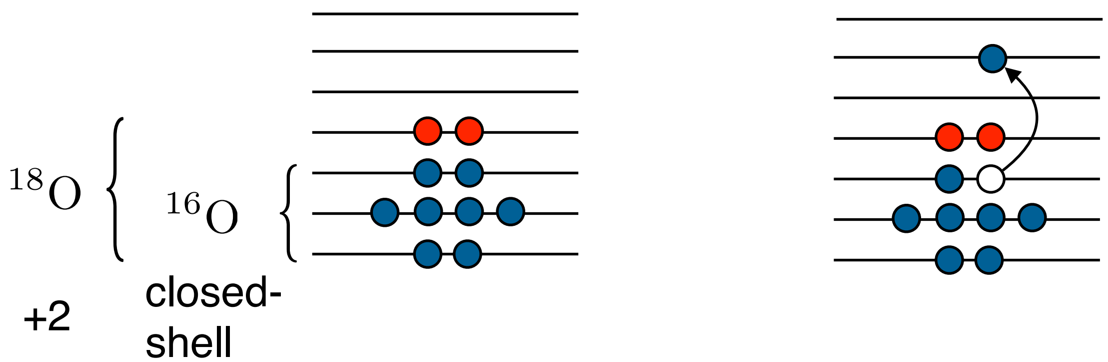
Outlook

Substantial progress in first principle calculations of electroweak reactions

- B04 in **2FP**: Two-particle attached technique (lead by F. Bonaiti)

$$\mathcal{R}(z)|\Phi_0\rangle = \left(\frac{1}{2}\sum_{ab} r^{ab}(z)\, a_a^\dagger a_b^\dagger + \frac{1}{6}\sum_{abci} r_i^{abc}(z)\, a_a^\dagger a_b^\dagger a_c^\dagger a_i + \dots\right)|\Phi_0\rangle$$

closed-shell



Very preliminary: m_0 (^{18}O)= 3.96 fm^2 (Nmax=4)

- **3FP**: Develop two-particle removed and one-particle removed/attach techniques to support the NEPTUNE program (^{6}Li, ^{14}N, ^{39}K besides ^{16}O)

See talk by Martin Baumann

Thanks to all my collaborators:

SFB Colleagues +

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

Thanks for your attention!