Ab initio Electroweak Reactions with Nuclei

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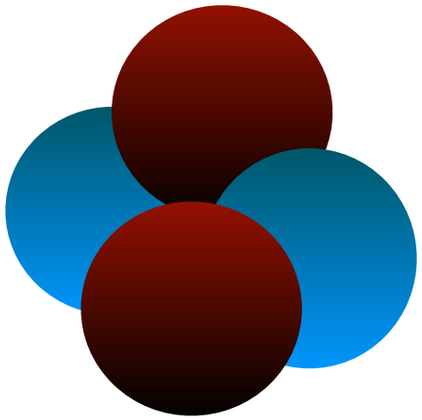
Ab initio nuclear theory

- 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

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

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

using interactions from chiral effective field theory

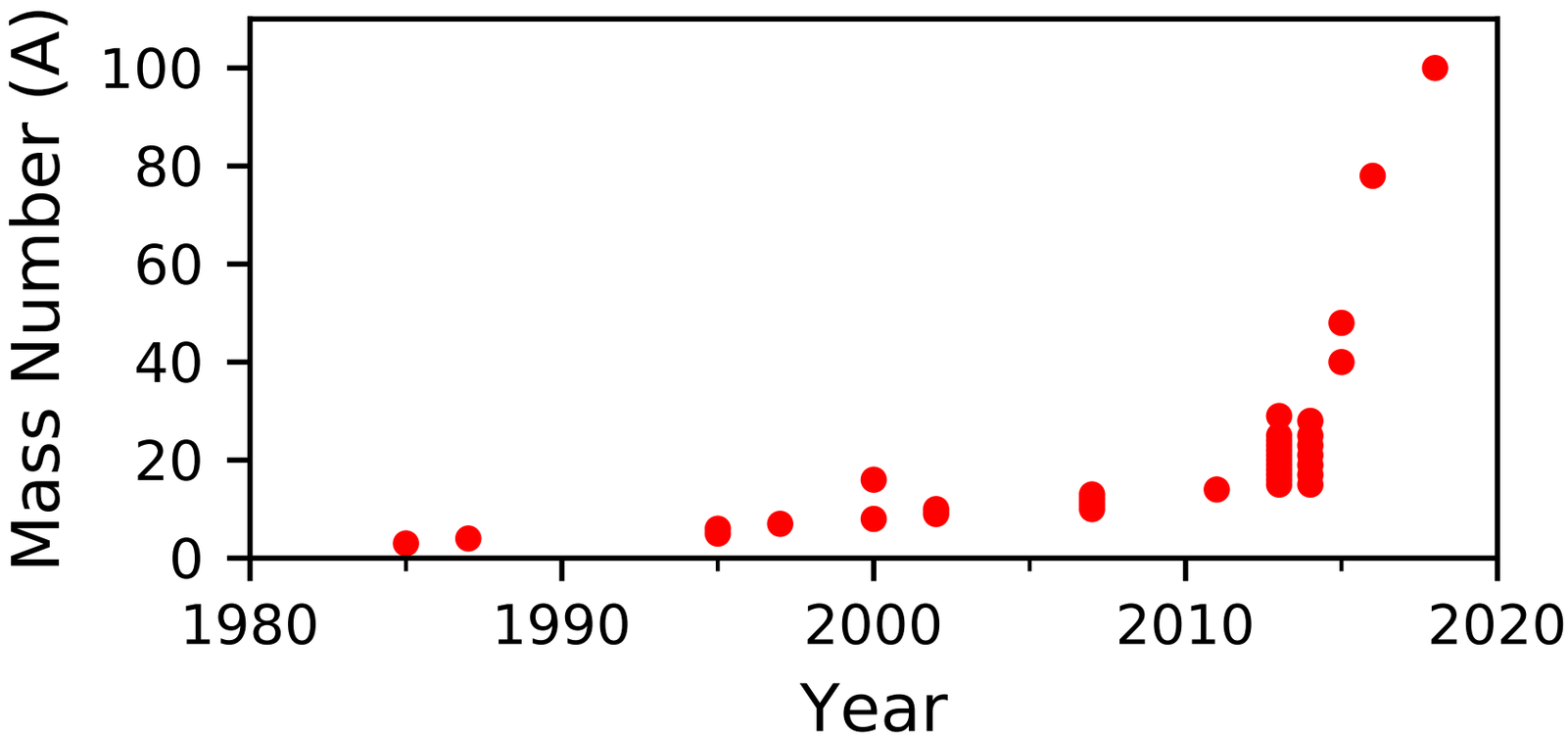
- Find numerical solutions with no approximations or controllable approximations

Progress of ab initio theory

^{208}Pb

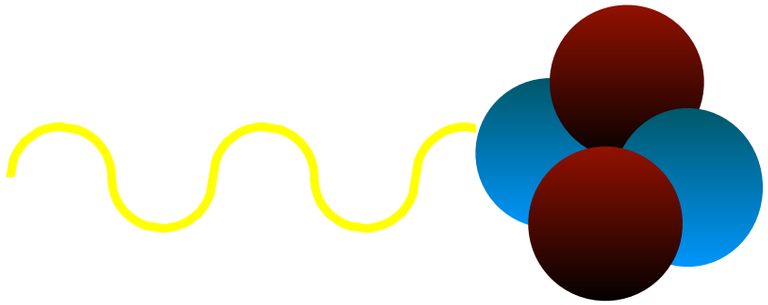
arXiv:2112.01125

Ab initio calculations starting from NN+3N interactions



J.Simonis, SB, G.Hagen, Eur. Phys. J. A **55**, 241 (2019).

Coupling to the em field



Cross Section

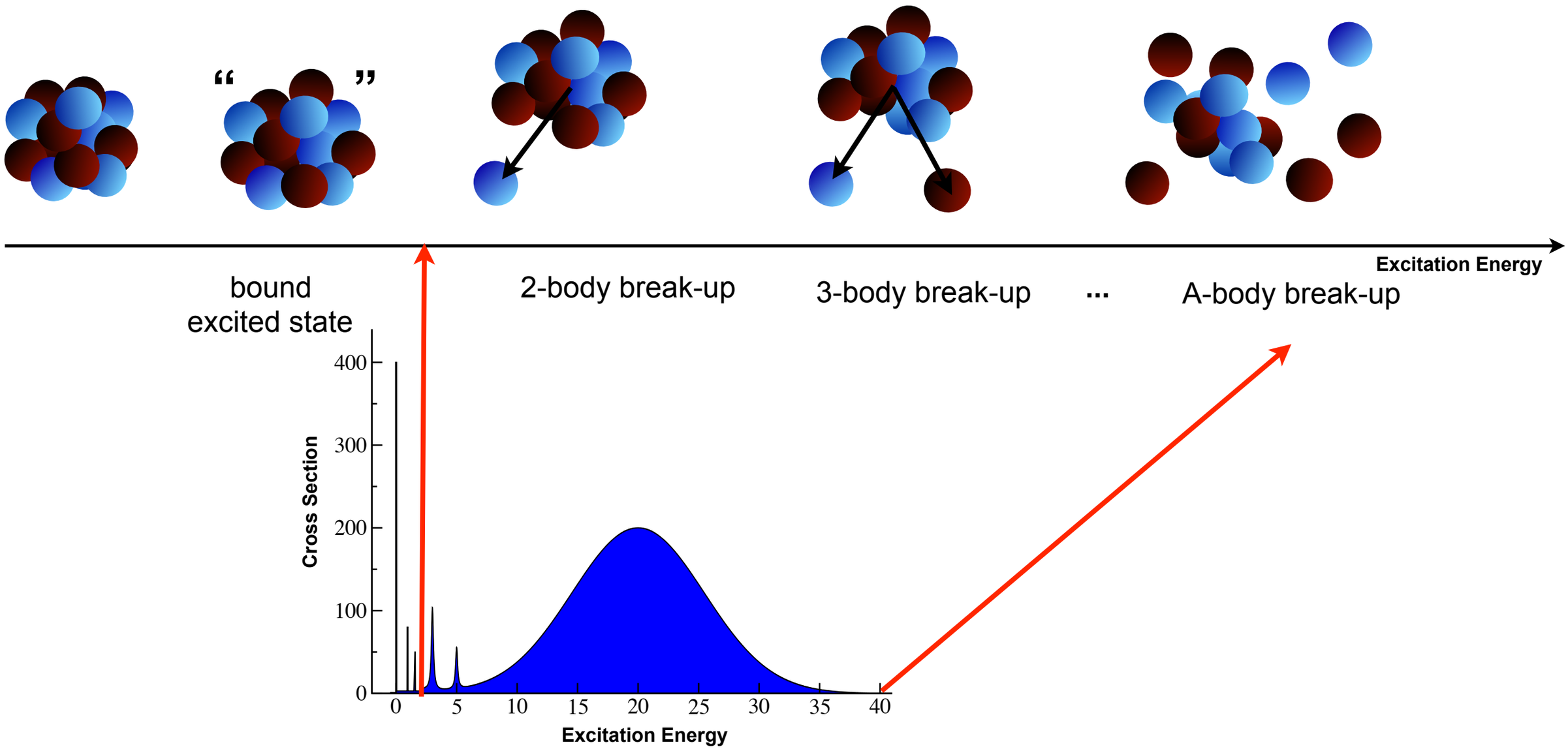
$$\sigma_{em} \sim R(\omega) = \sum_f \left| \left\langle \psi_f \left| \Theta \right| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$$

Electroweak operator

The continuum problem

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

Depending on E_f, many channels may be involved



Integral Transforms

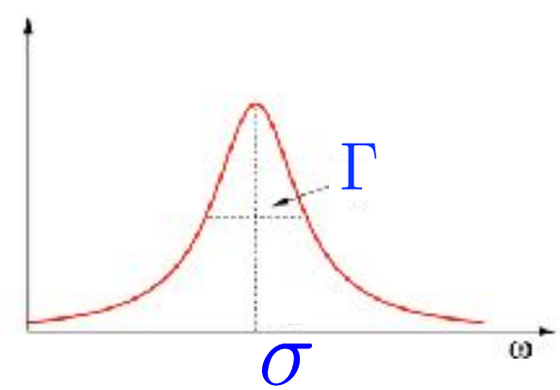
$$R(\omega) = \sum_f \left| \langle \psi_f | \Theta | \psi_0 \rangle \right|^2 \delta(E_f - E_0 - \omega)$$

Exact knowledge limited in energy and mass number

Lorentz Integral Transform

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

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



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

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

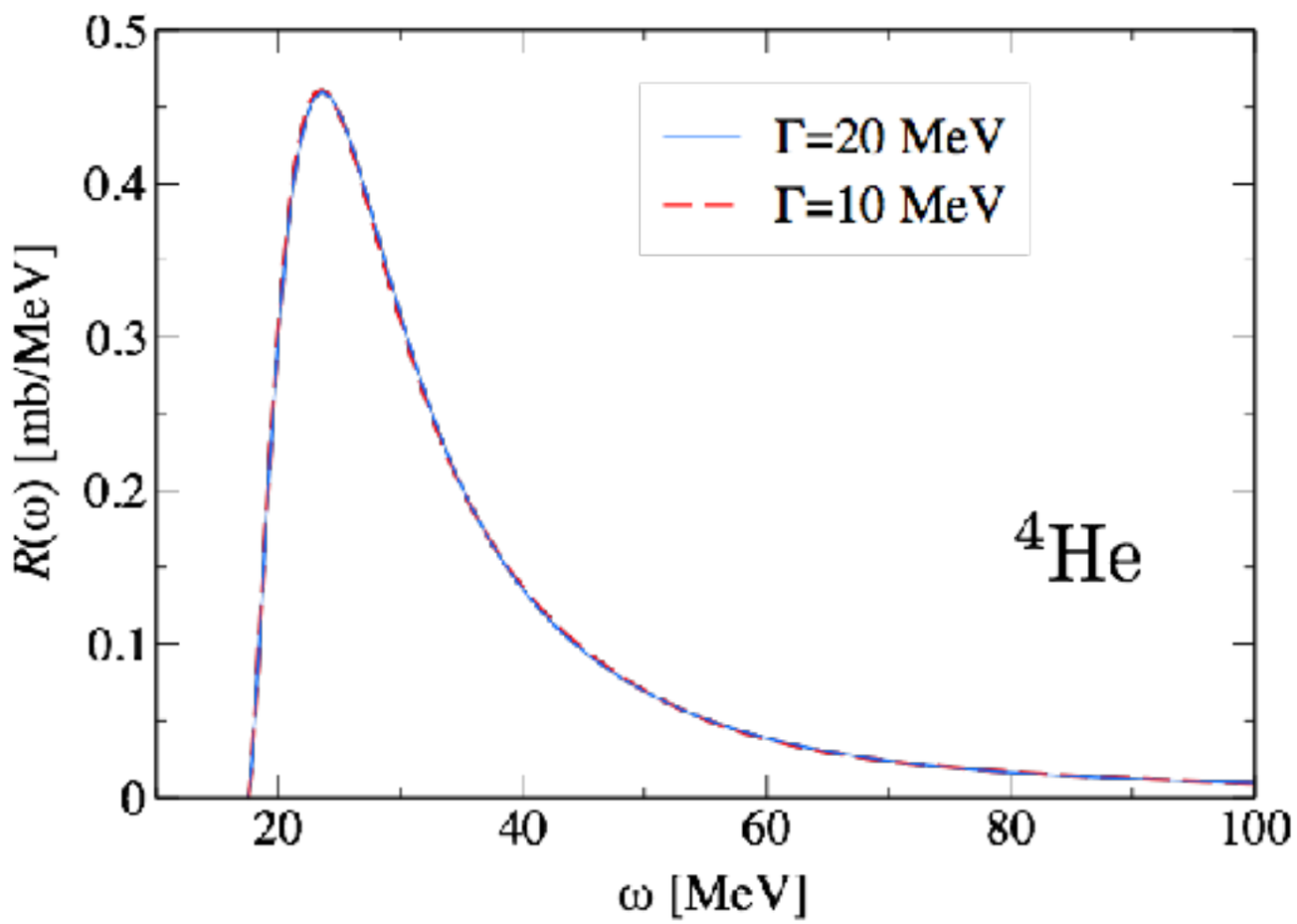
Inversion of the LIT

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



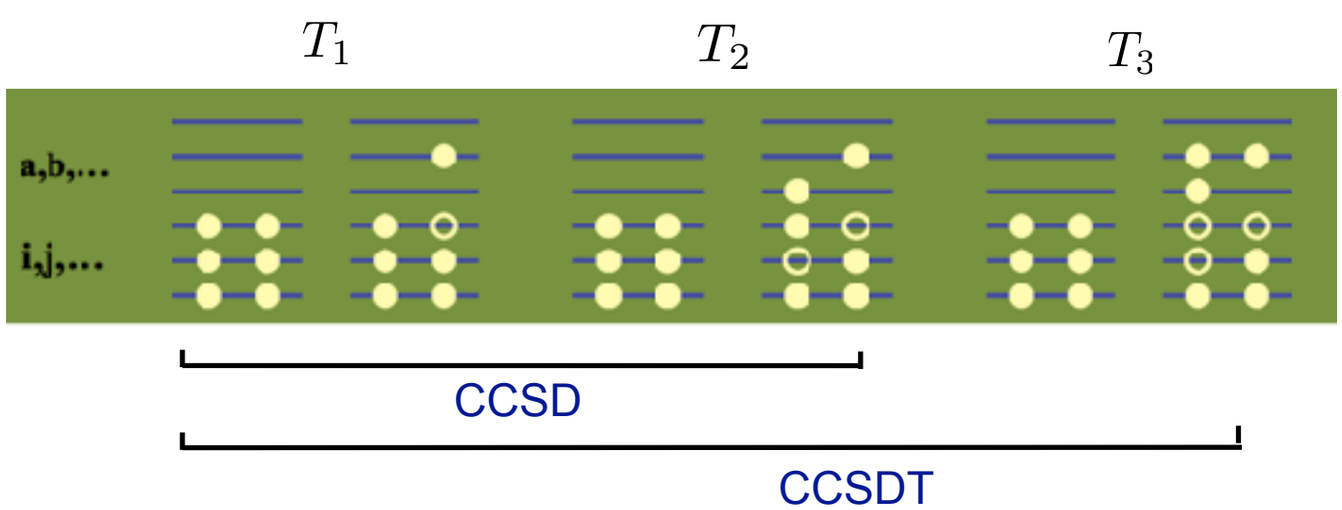
Message: Inversions are stable if the LIT is calculated precisely enough

Coupled-cluster theory formulation

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

$$T = \sum T_{(A)}$$

cluster expansion



See also
G. Hagen's talk

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

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

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

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

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

Results with implementation at CCSD level

$$T = T_1 + T_2$$

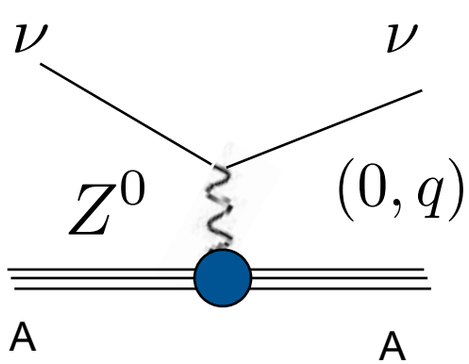
$$R = R_0 + R_1 + R_2$$

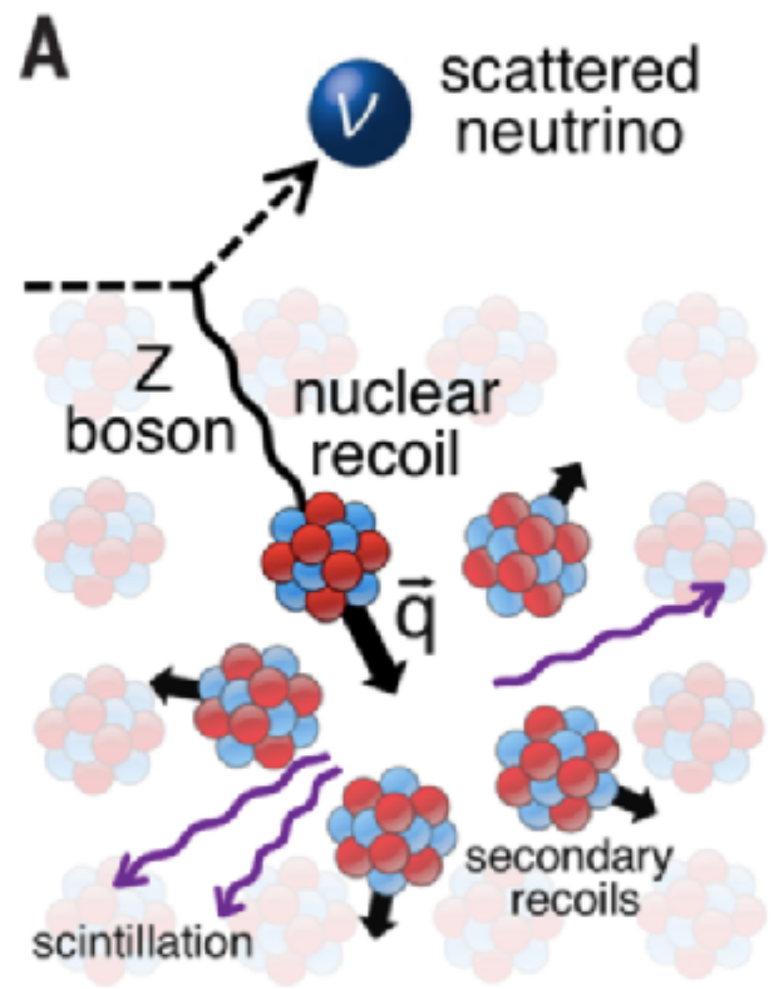
+ some study of triples contributions

Applications to lepton-nucleus scattering

CEνNS

Coherent elastic neutrino scattering





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

This is valid for neutrino energies up to 50 MeV

Experimental signature: tiny energy deposited by nuclear recoils in the target material

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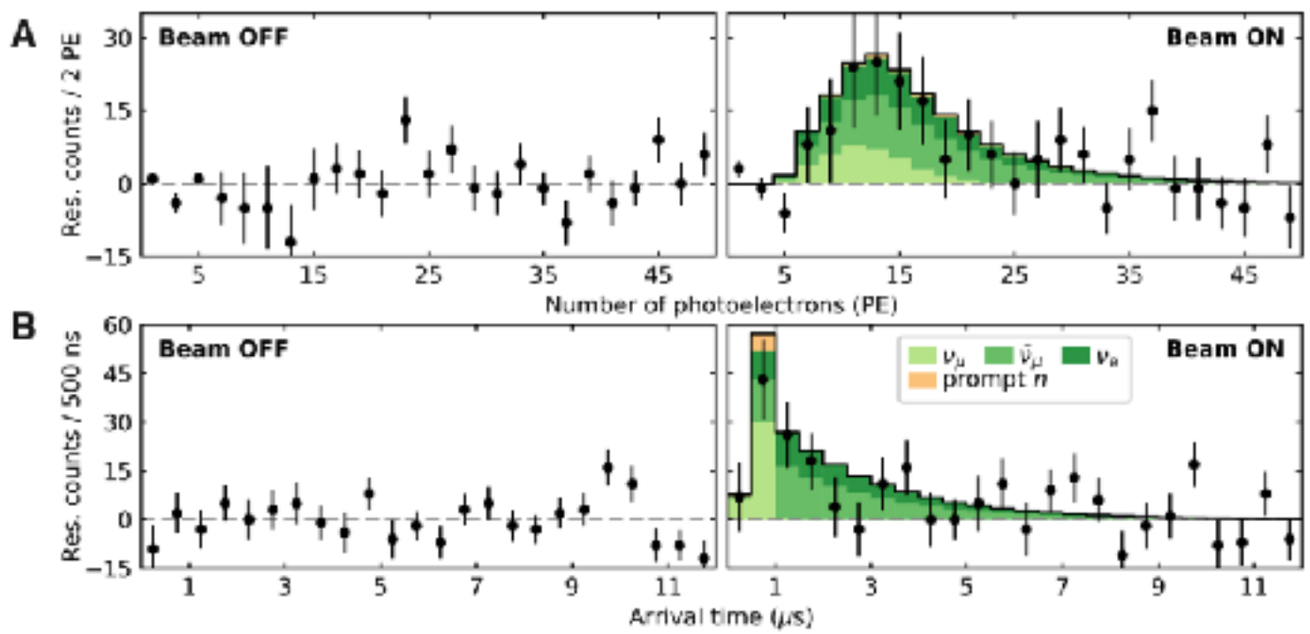
REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering



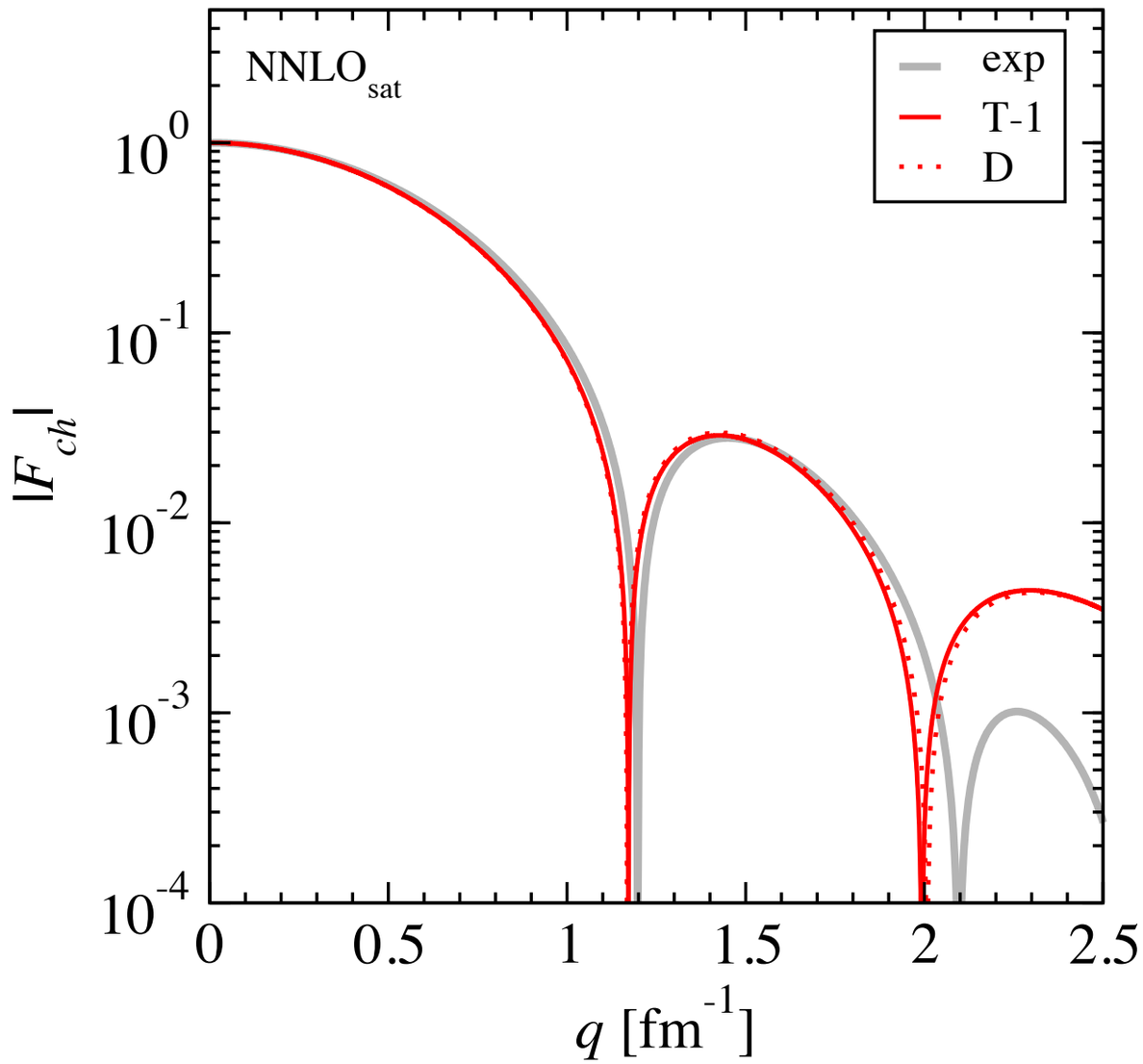
$$\frac{d\sigma}{dT}(E_\nu, T) \simeq \frac{G_F^2}{4\pi} M \left[1 - \frac{MT}{2E_\nu^2}\right] Q_W^2 F_W^2(q^2)$$

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

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

^{40}Ar Form Factors

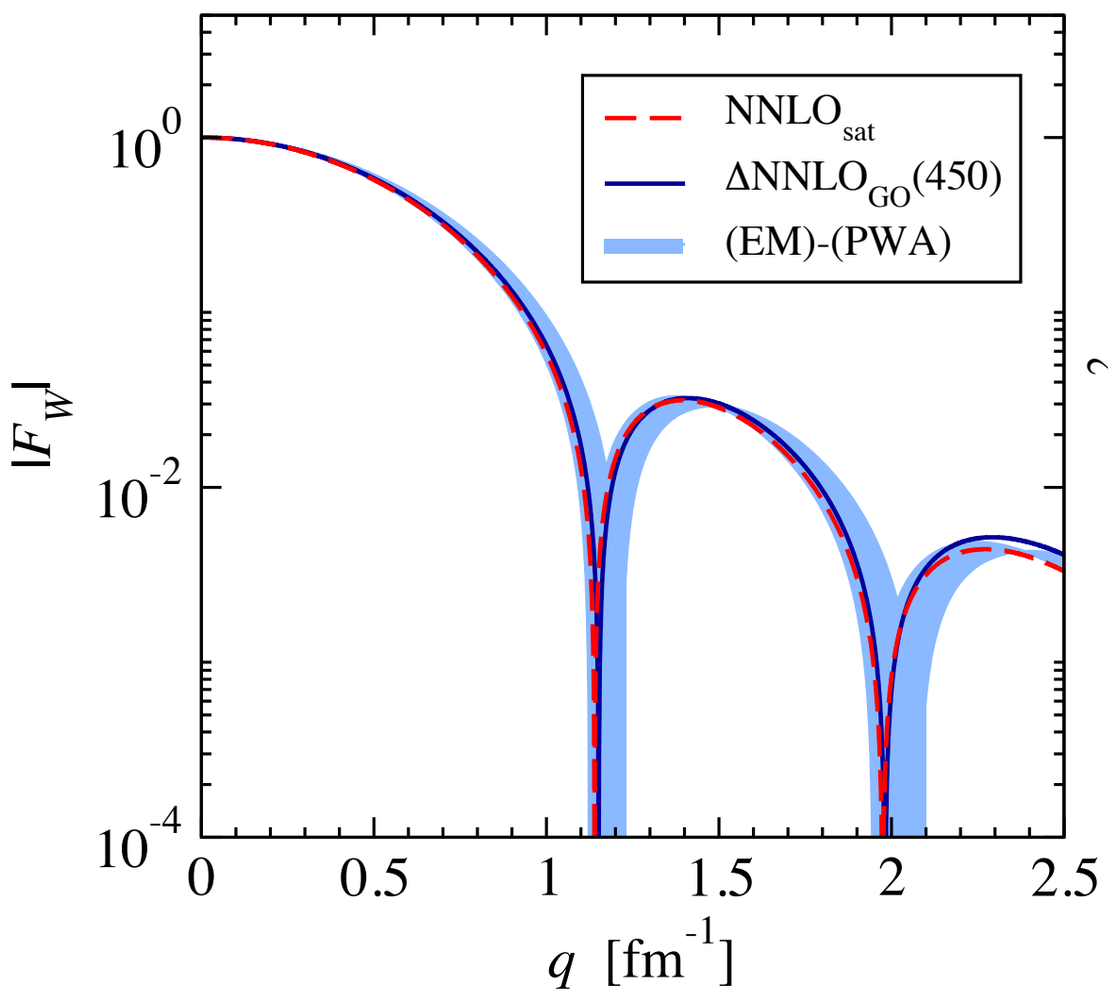
C. Payne et al., Phys. Rev. C **100**, 061304(R) (2019)

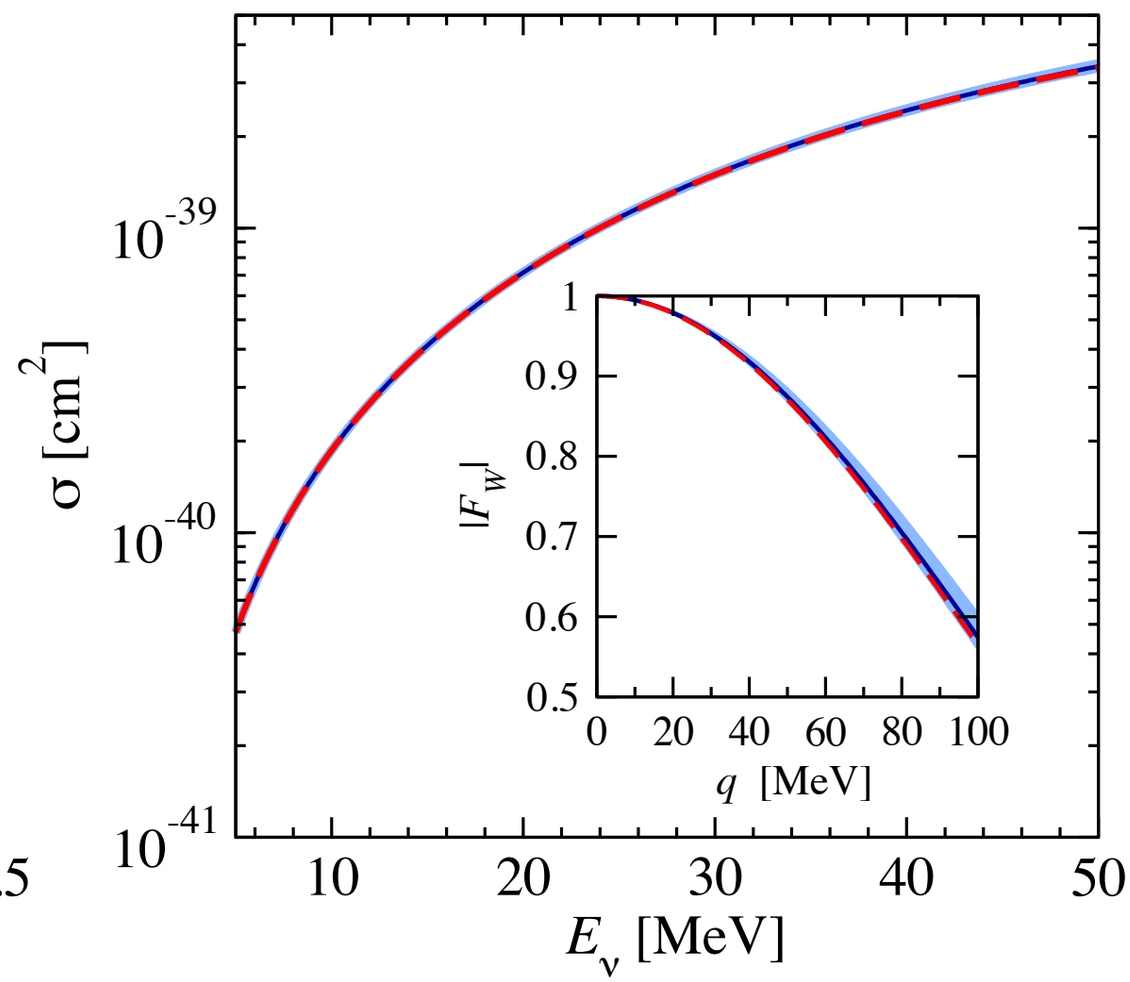


exp: in Mainz, Ottermann et. al., Nucl. Phys. A **379**, 396 (1982)

^{40}Ar Form Factors

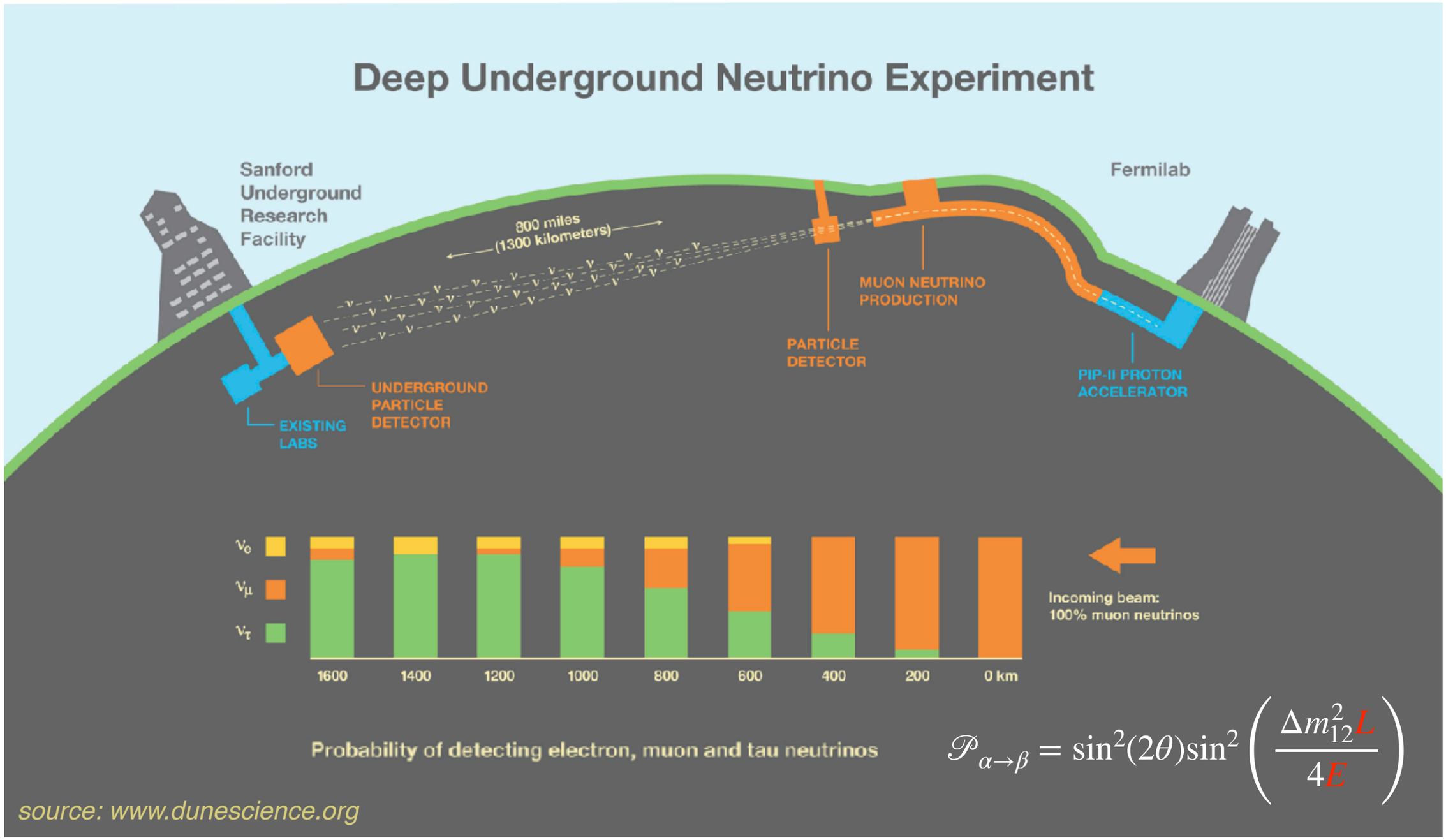
C. Payne et al., Phys. Rev. C **100**, 061304(R) (2019)





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

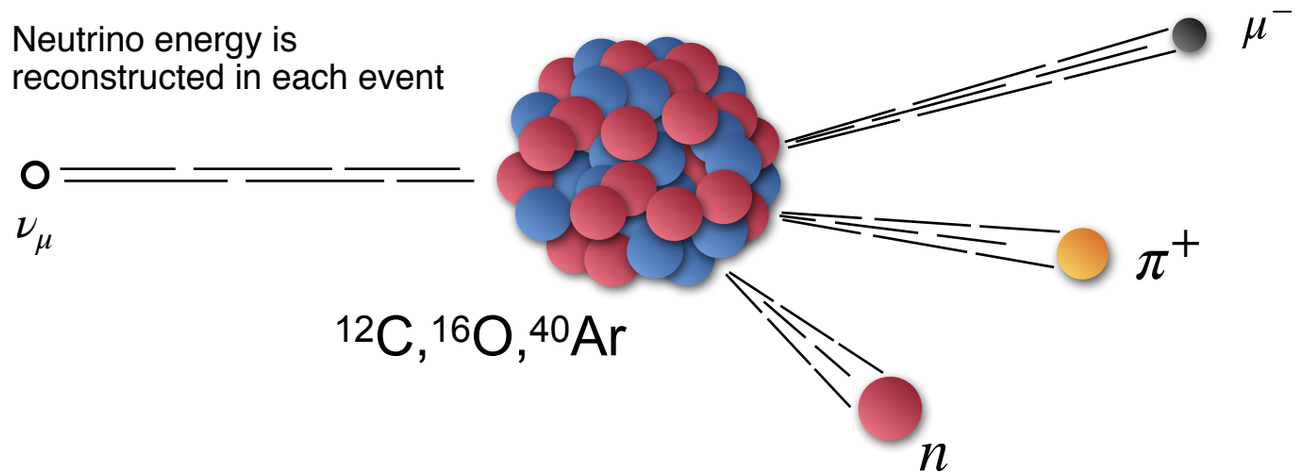
Neutrino Oscillations

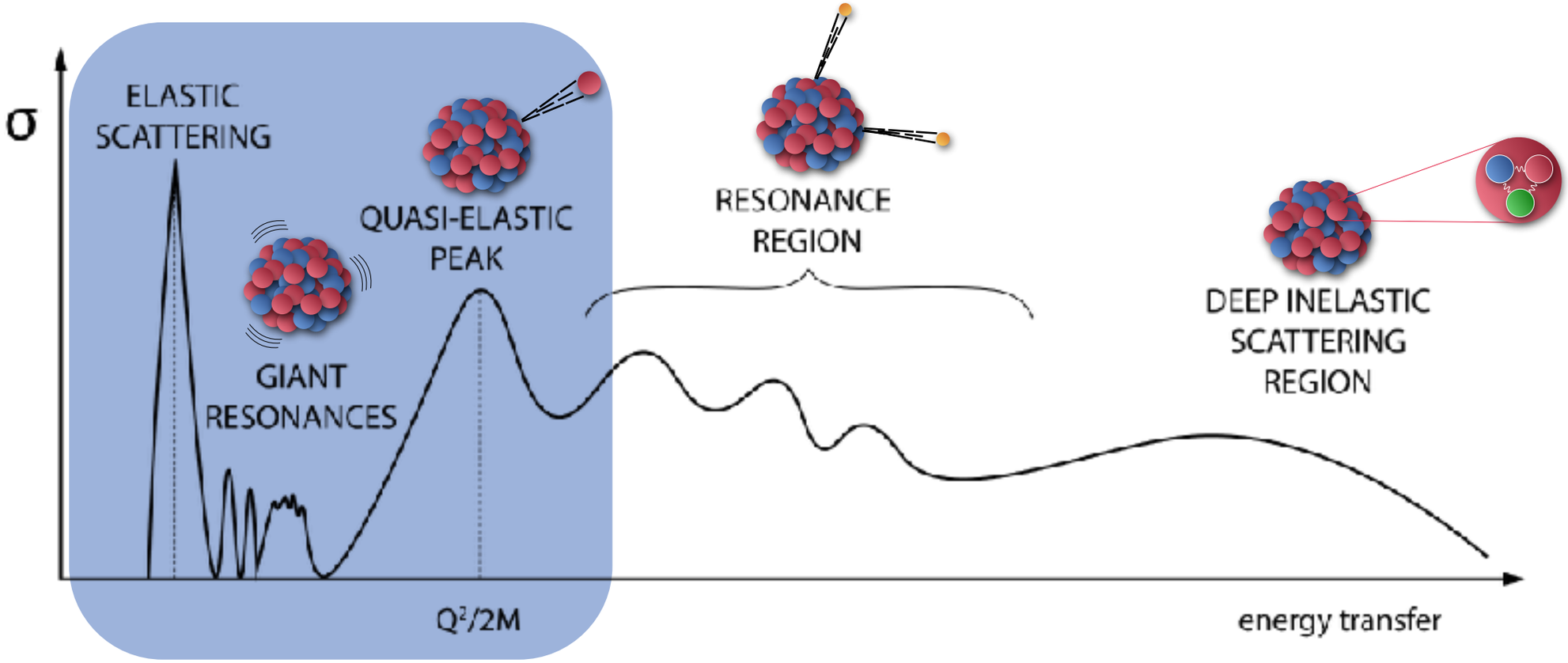


$$\mathscr{P}_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{12} L}{4E}\right)$$

source: www.dunescience.org

Aims and challenges





Electrons and neutrinos

ν-A scattering

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

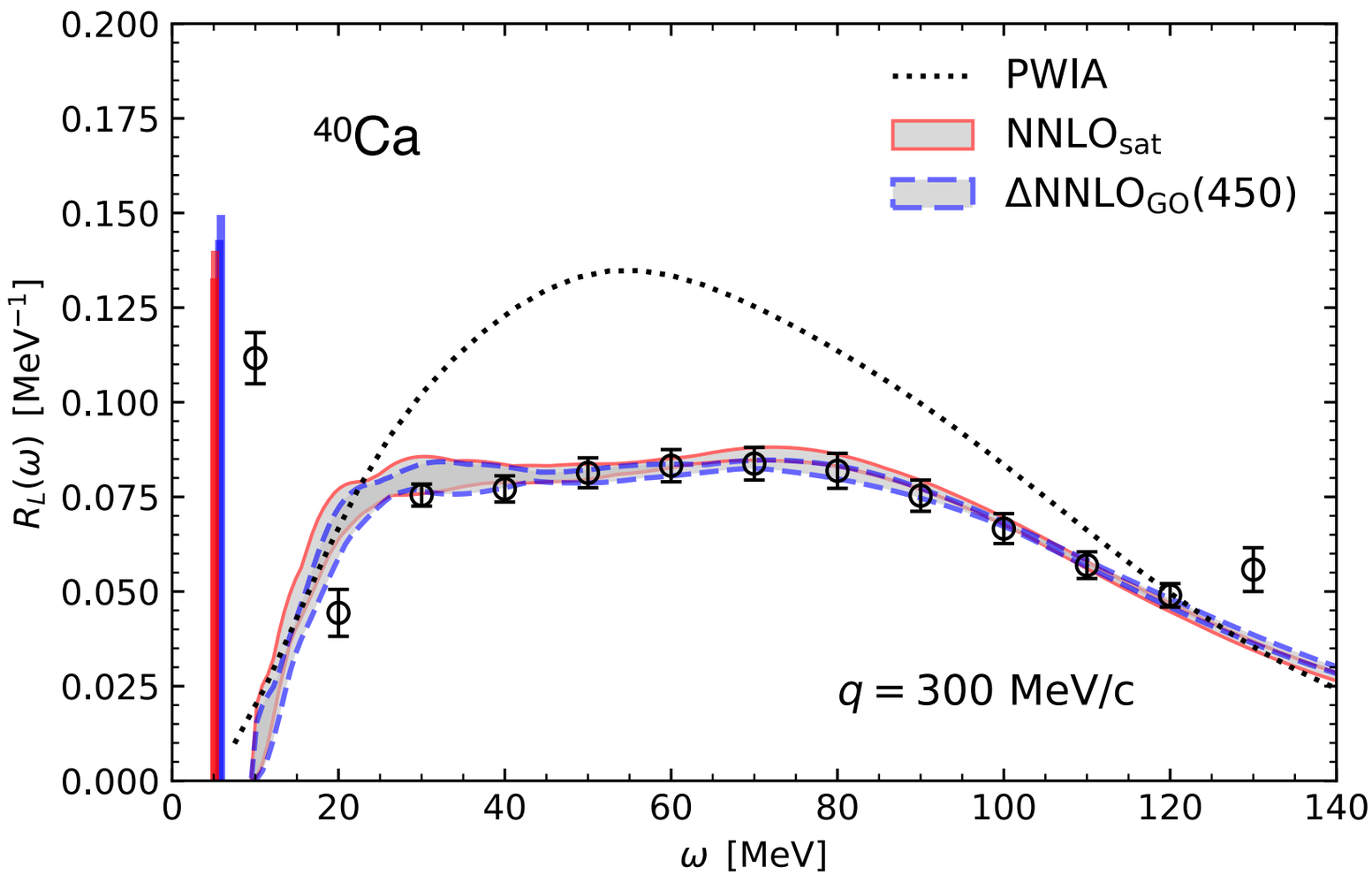
e-A scattering

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

Recent Highlights on (e,e')

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

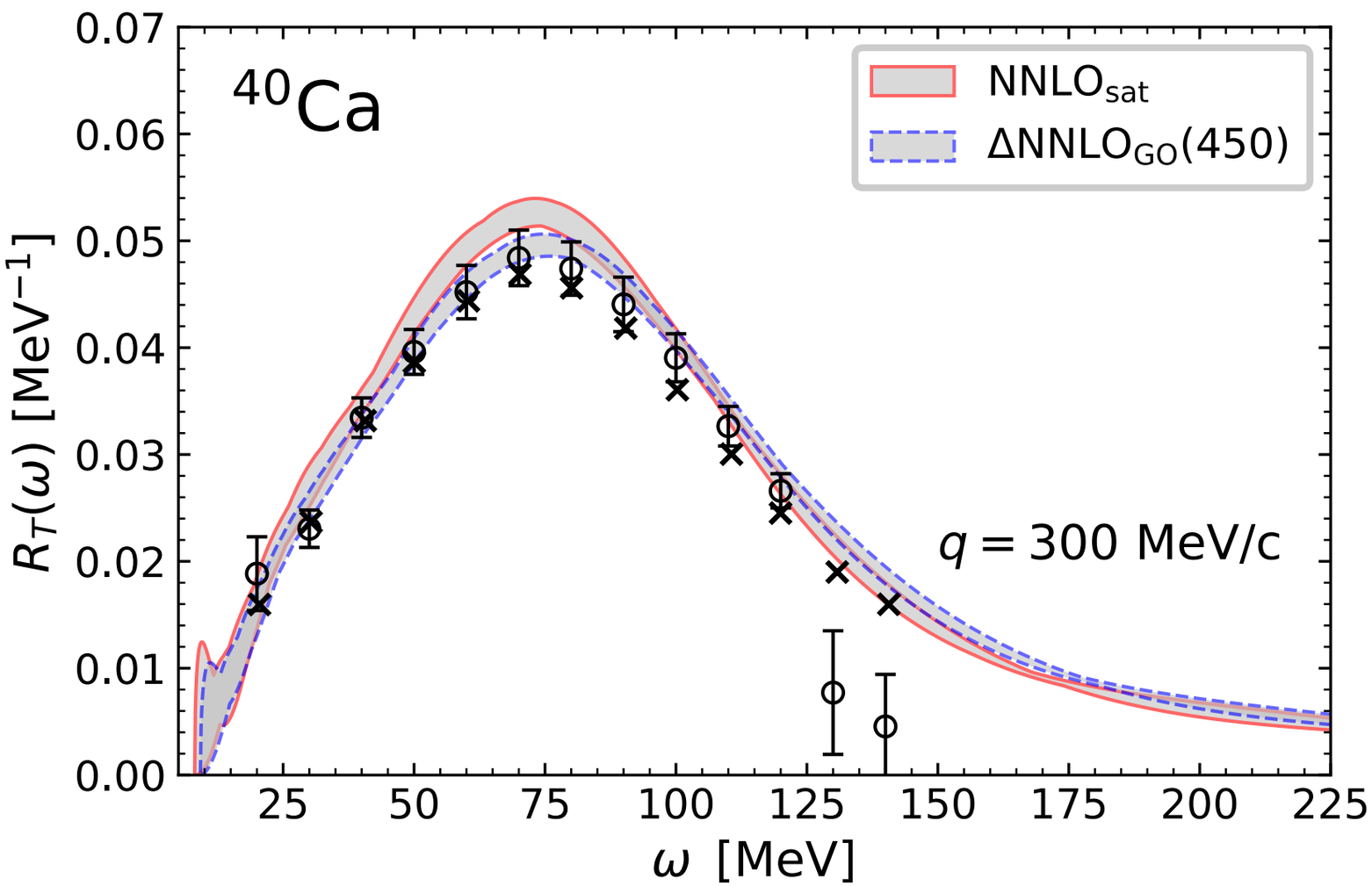
Sobcyzk, Acharya, Bacca, Hagen, PRL **127** (2021) 7, 072501



Recent Highlights on (e,e')

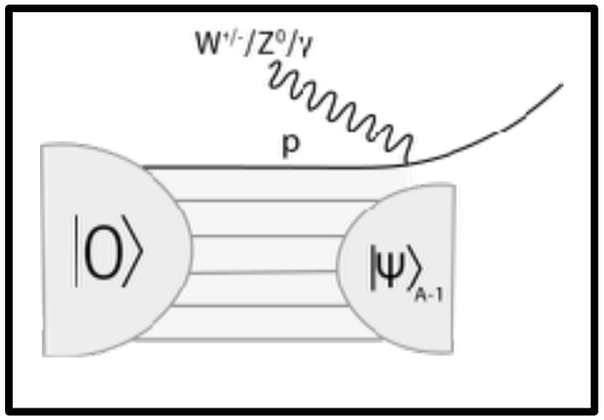
Inelastic transverse response function

Acharya, Sobcyzk, Bacca, Hagen, in preparation

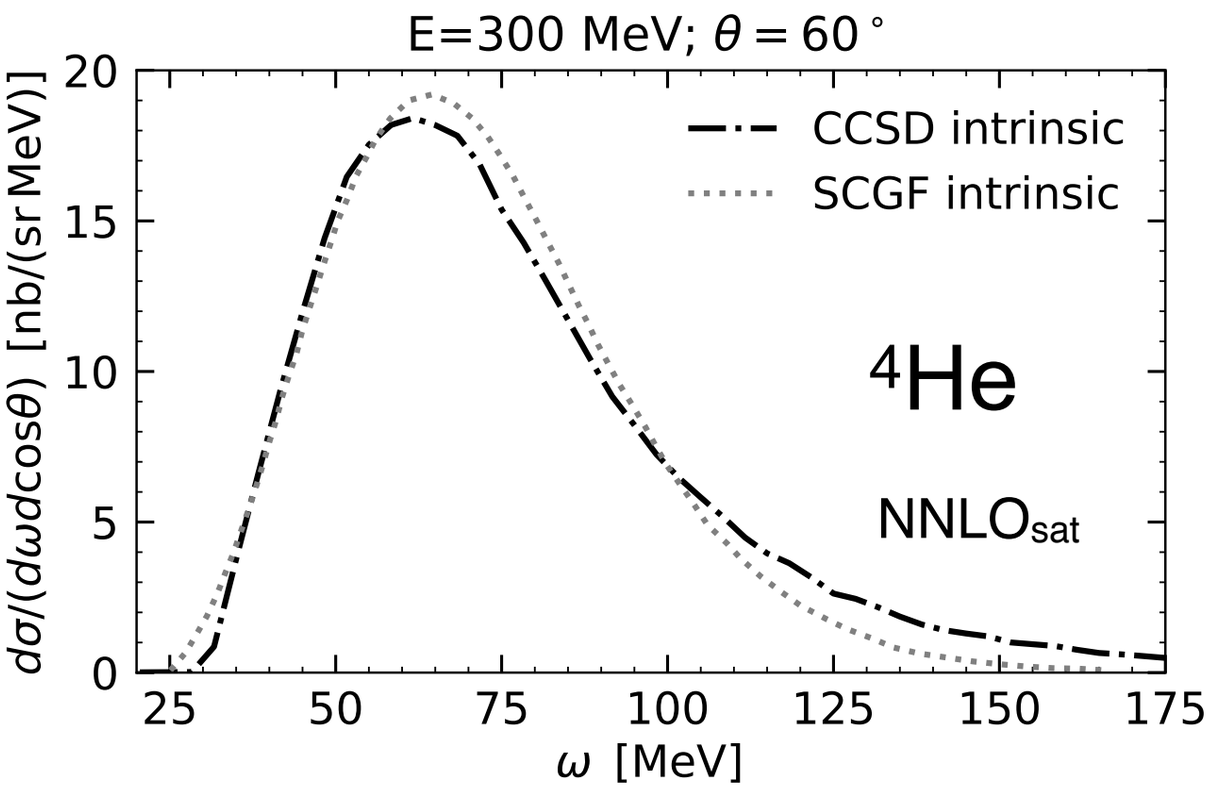


Recent Highlights on (e,e')

Access higher energies with Spectral Functions

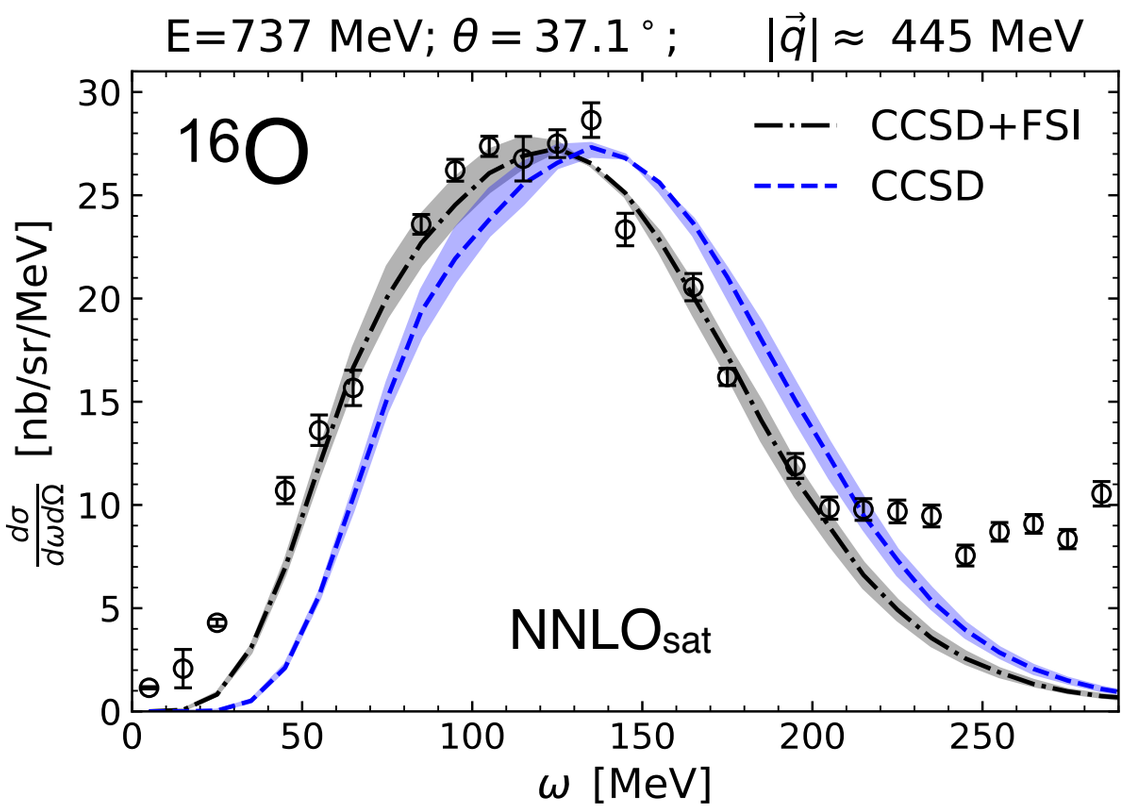


Sobcyzk, SB, Hagen, Papenbrock, to appear on PRC (2022)



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

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



Outlook

- Remarkable progress in first principle calculations of electroweak reactions
- More work to be expected in the neutrino sector. Stay tuned!

Thanks to all my collaborators:

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

Thanks for your attention!