Ab initio Electroweak Reactions with Nuclei

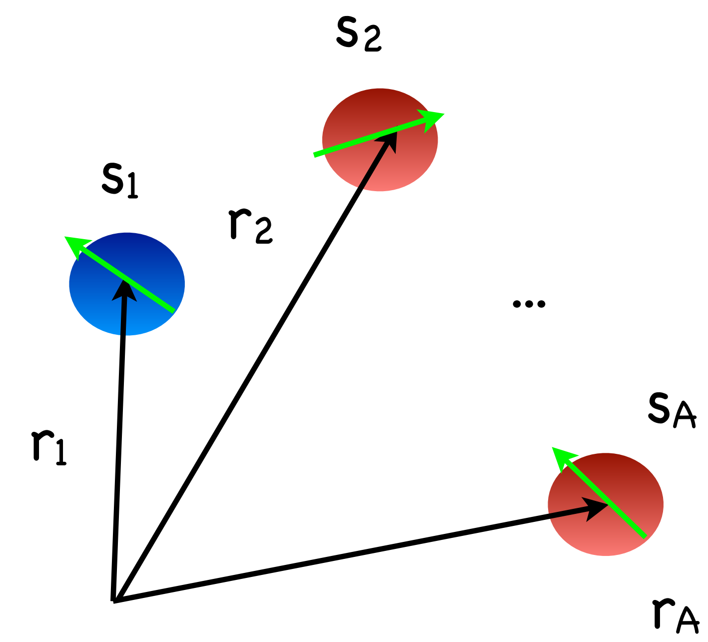
Sonia Bacca

Johannes Gutenberg Universität Mainz

May 16th, 2022

Ab initio nuclear theory

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



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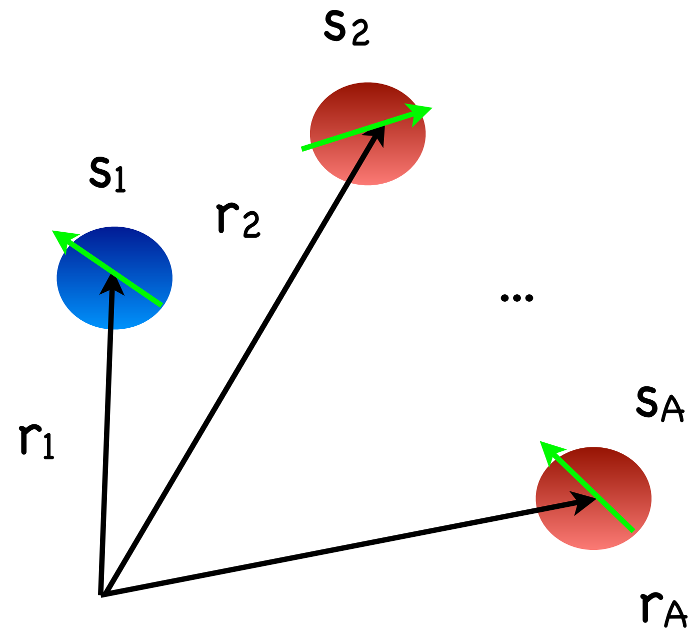

- Solve the non-relativistic quantum mechanical problem of A-interacting nucleons

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

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

using interactions from chiral effective field theory

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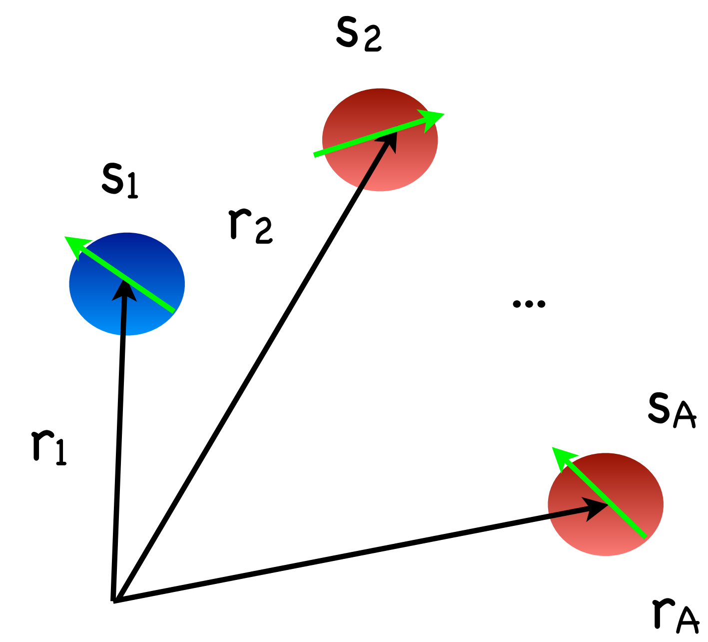

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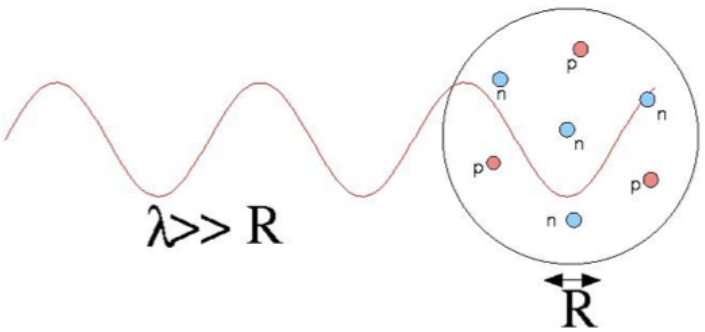
using interactions from chiral effective field theory

- Find numerical solutions with no approximations or controllable approximations

Chiral Effective Field Theory



Limited resolution at low energy

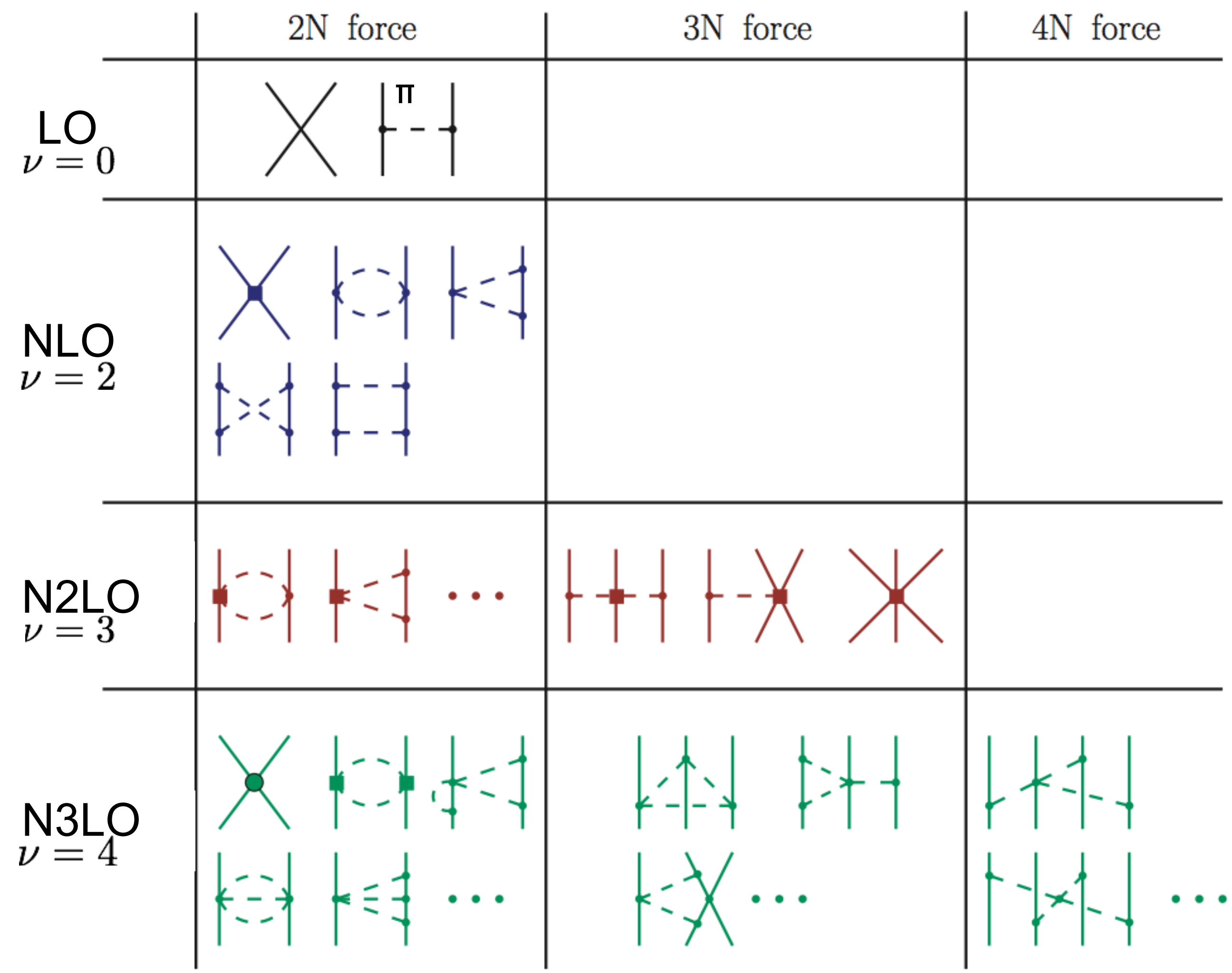
Separation of scales

$$\frac{1}{\lambda} = Q \ll \Lambda_b = \frac{1}{R}$$

Systematic expansion

$$\mathcal{L} = \sum_{\nu} c_{\nu} \left(\frac{Q}{\Lambda_b} \right)^{\nu}$$

Details of short distance physics not resolved, but captured in low energy constants (LEC)



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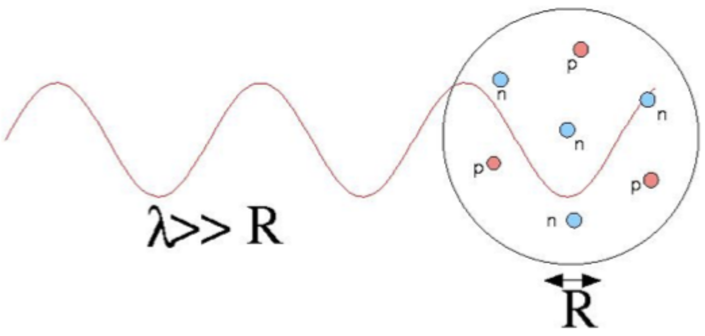

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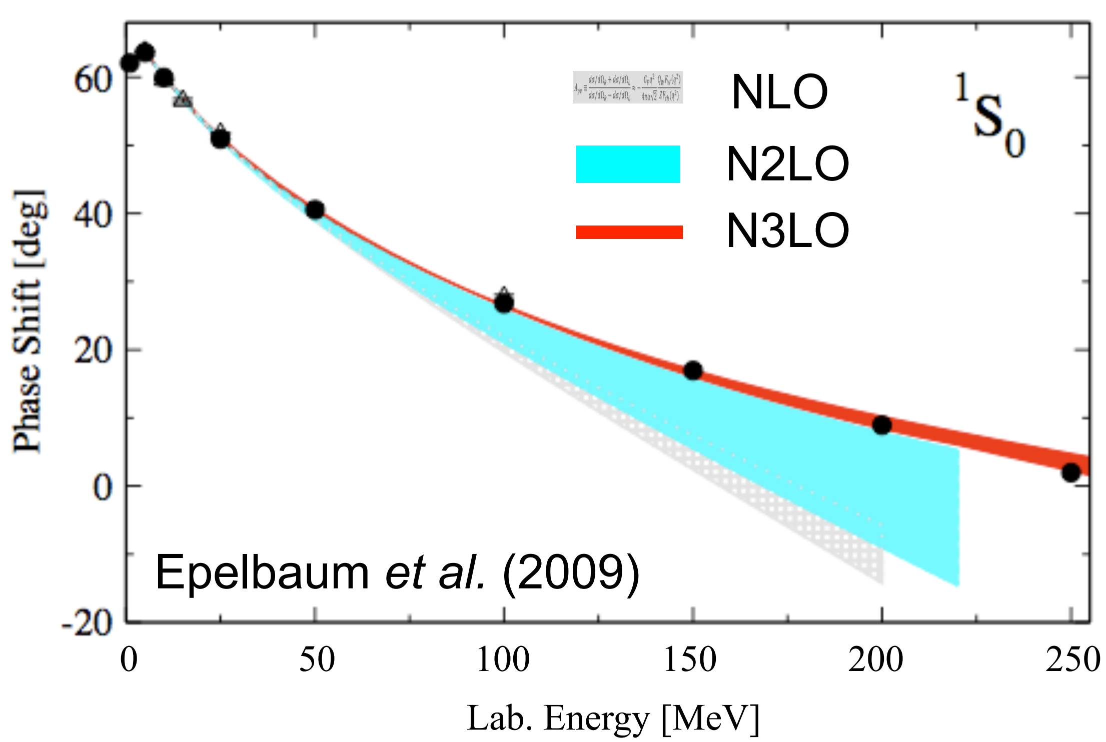
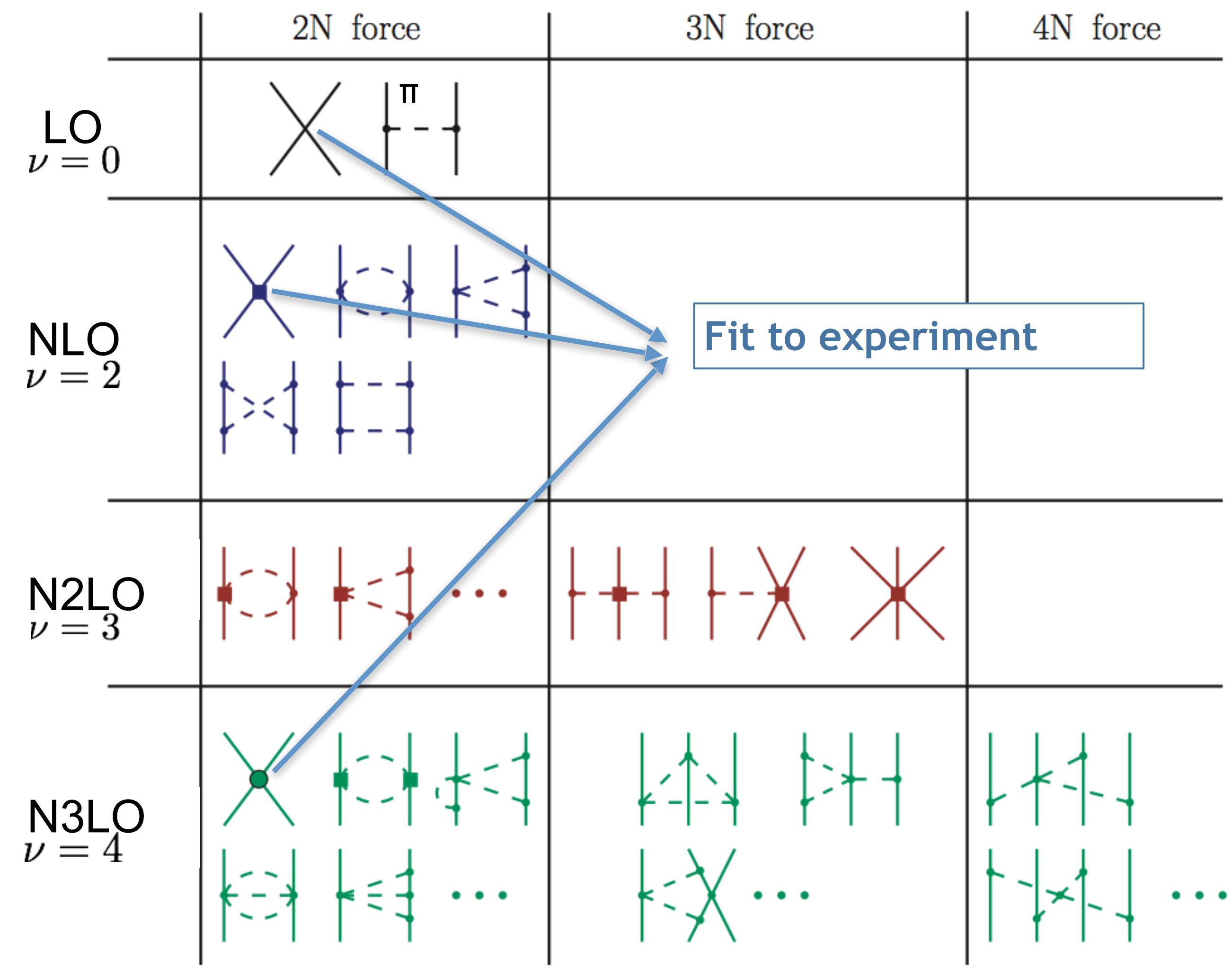
LEC fit to experiment - NN sector -





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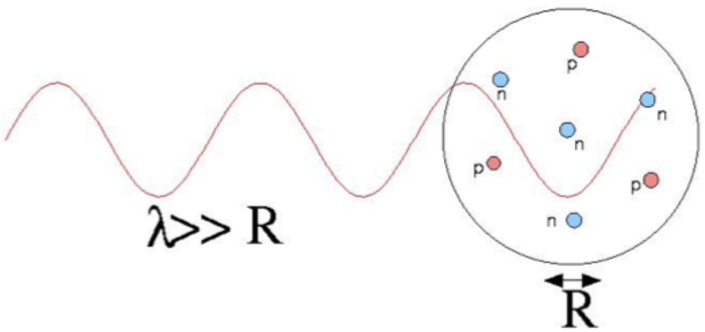

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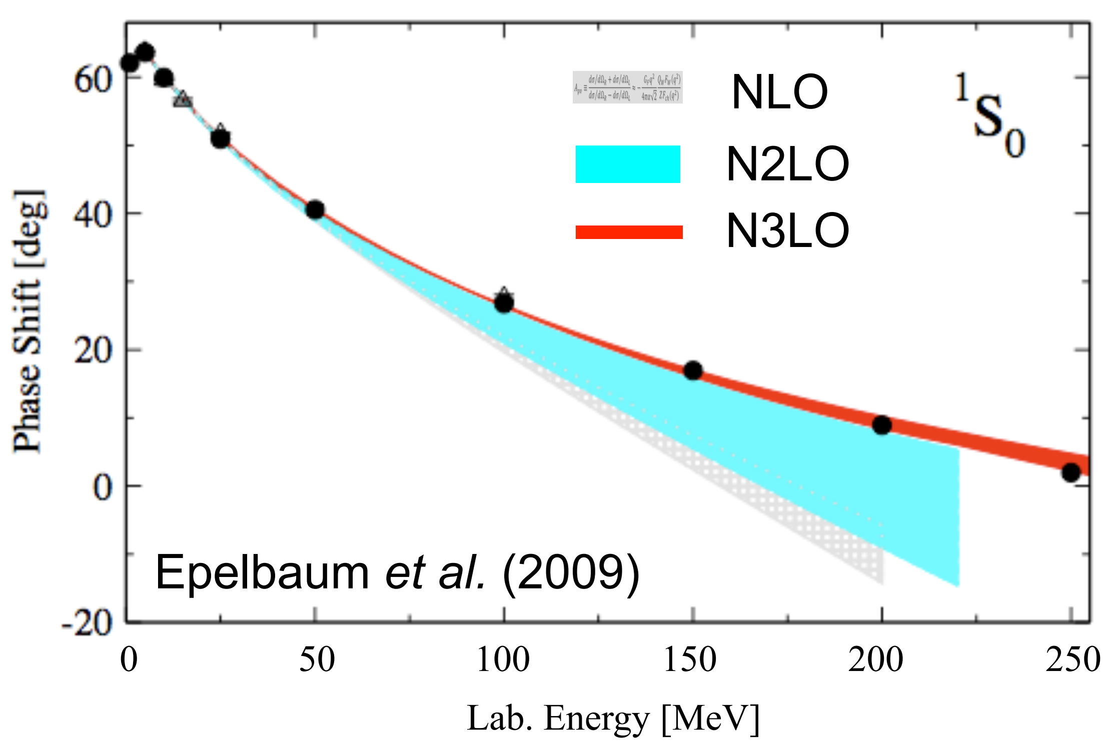
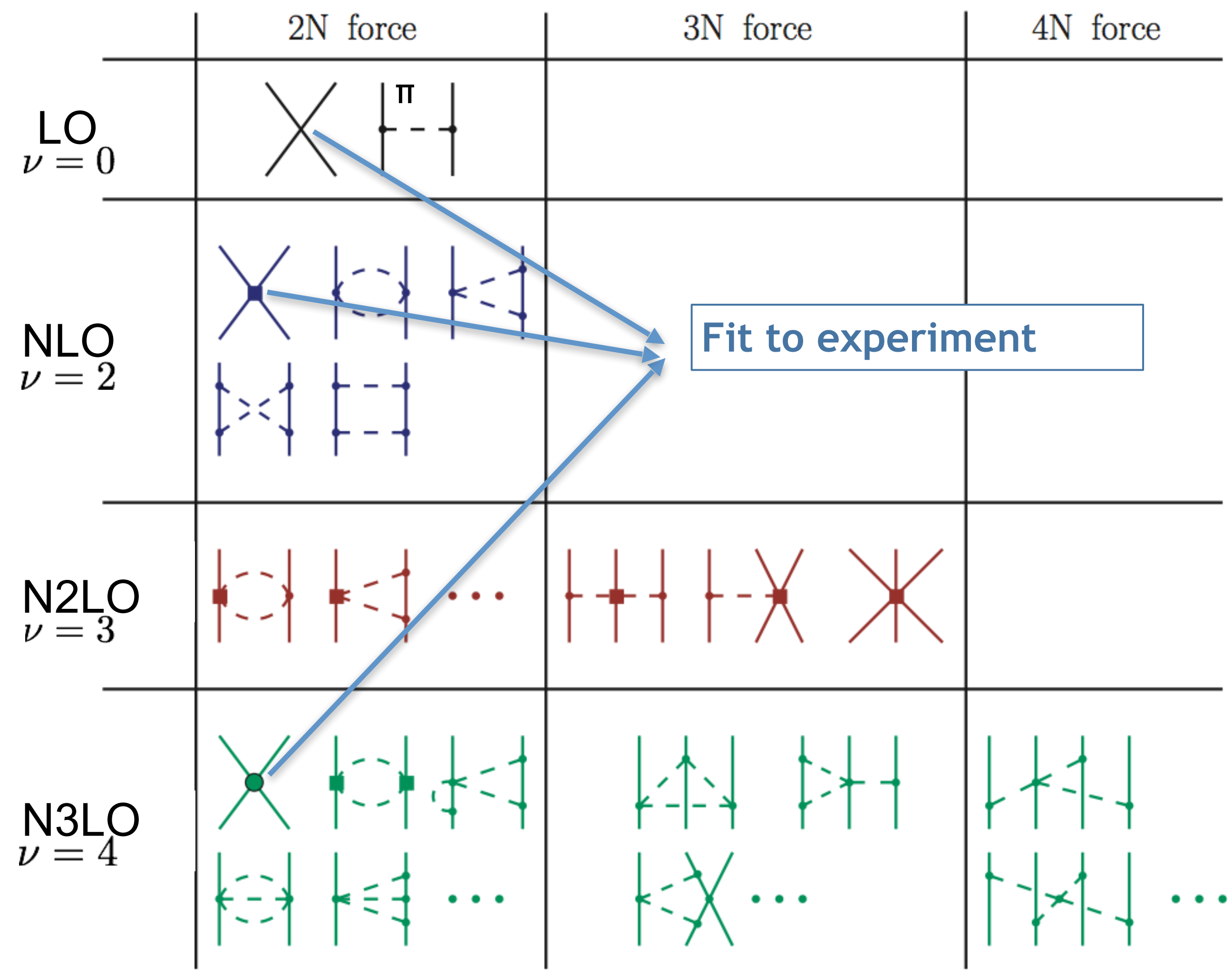
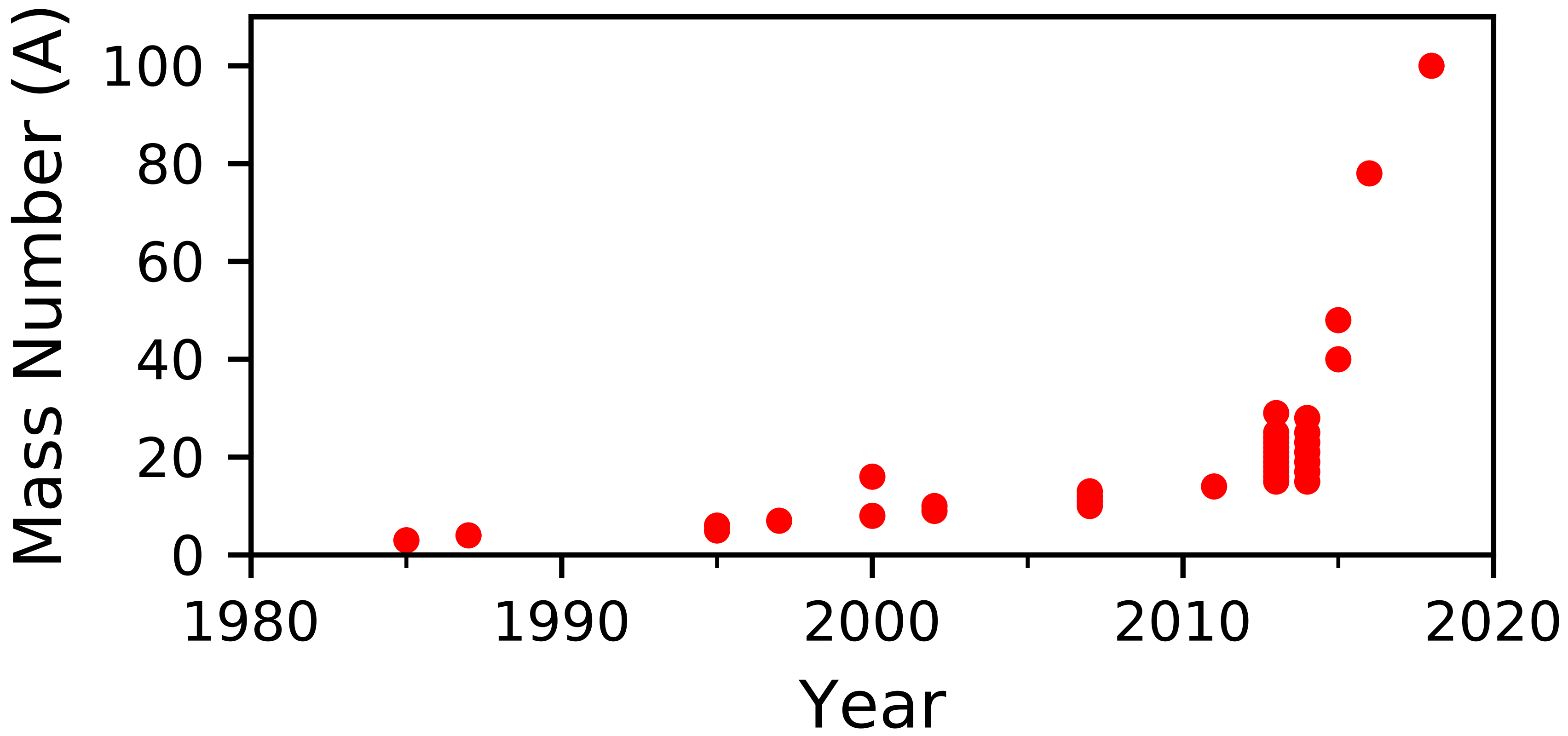




Calibrate Hamiltonian and then predict other observables

Progress of ab initio theory

Ab initio calculations starting from
NN+3N interactions



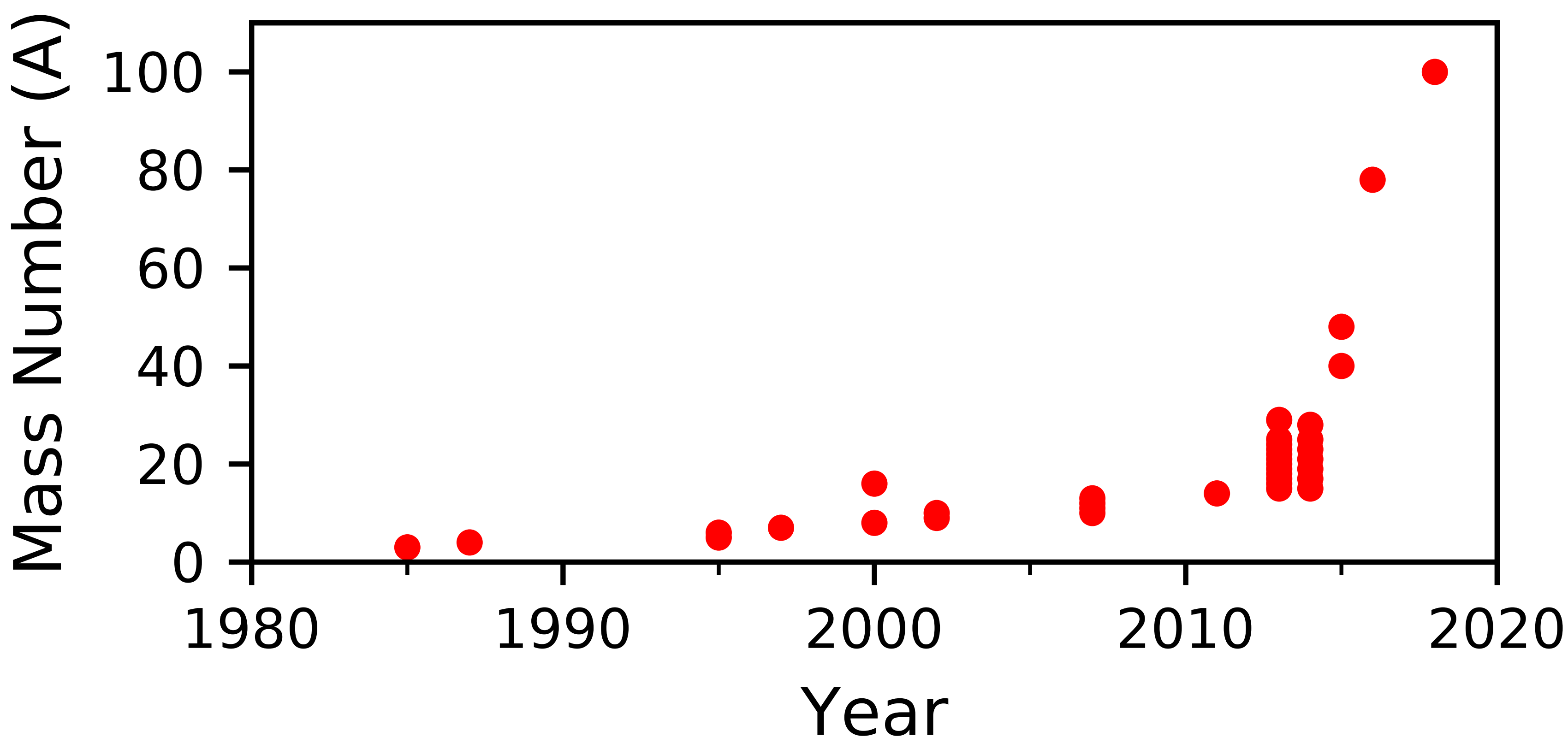
J.Simonis, SB, G.Hagen, Eur. Phys. J. A **55**, 241 (2019).

Progress of ab initio theory

^{208}Pb

arXiv:2112.01125

Ab initio calculations starting from NN+3N interactions



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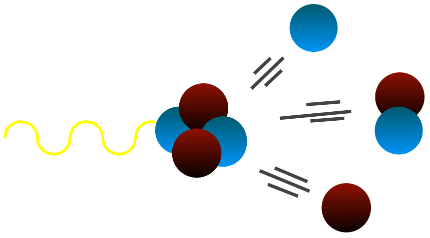
Electroweak reactions

- How does the nucleus respond to external electroweak excitations?



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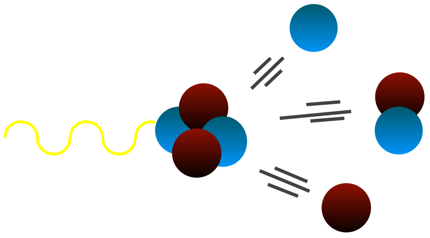

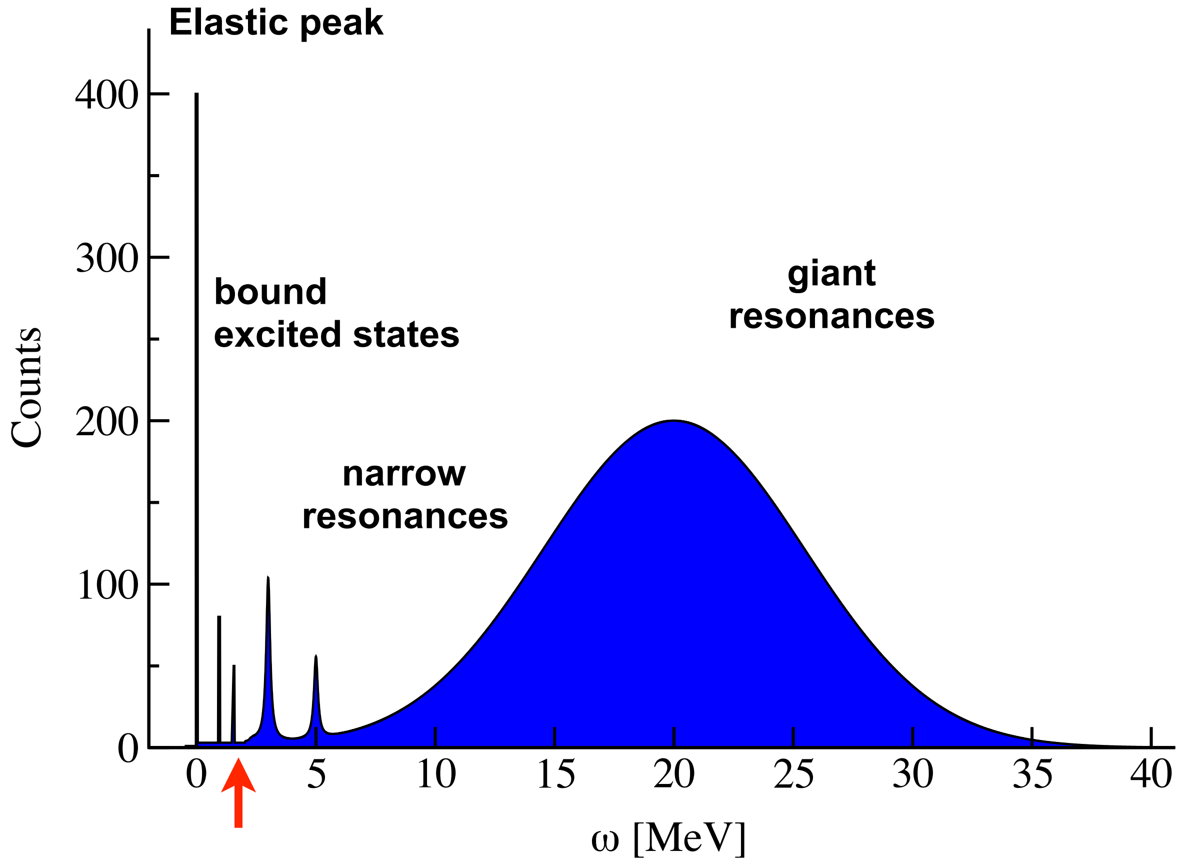

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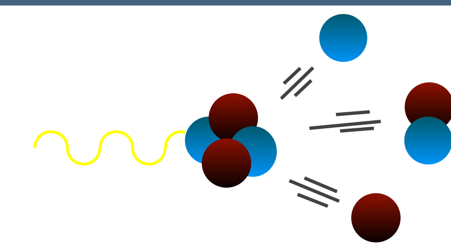

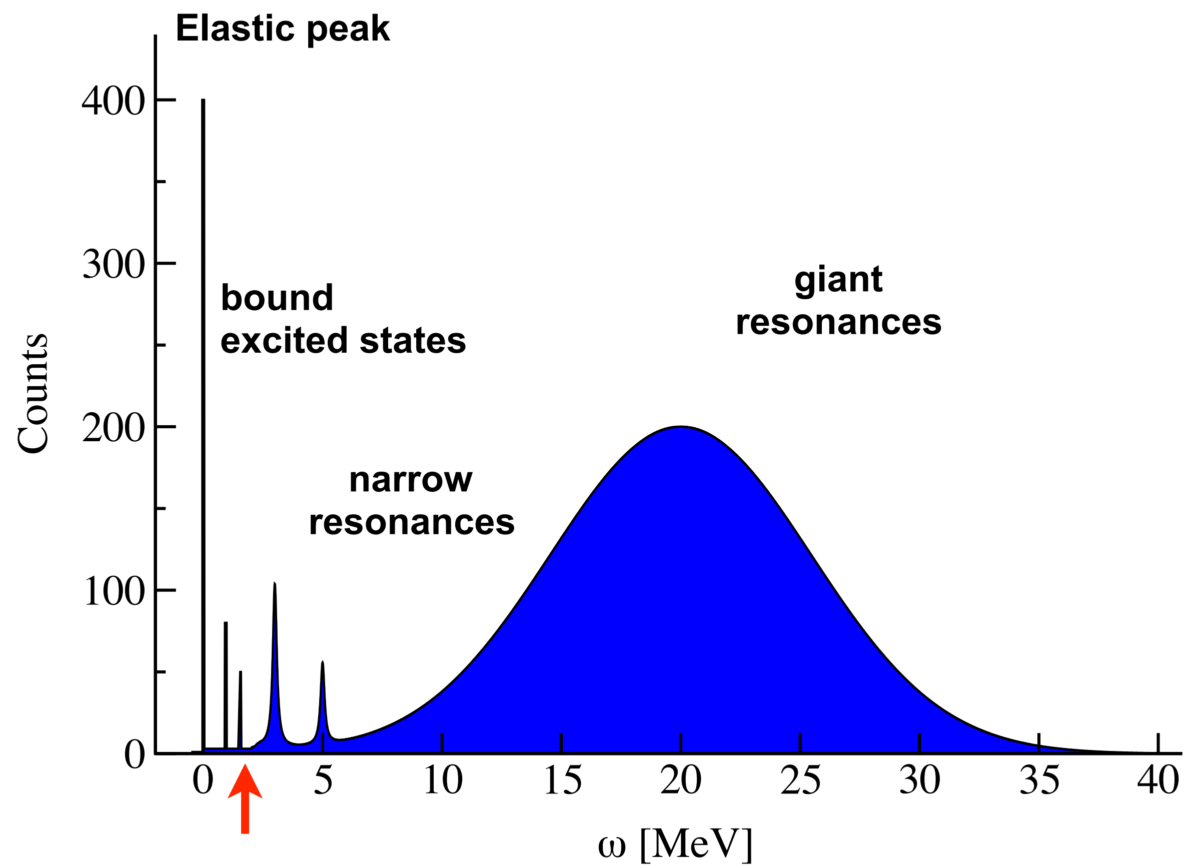

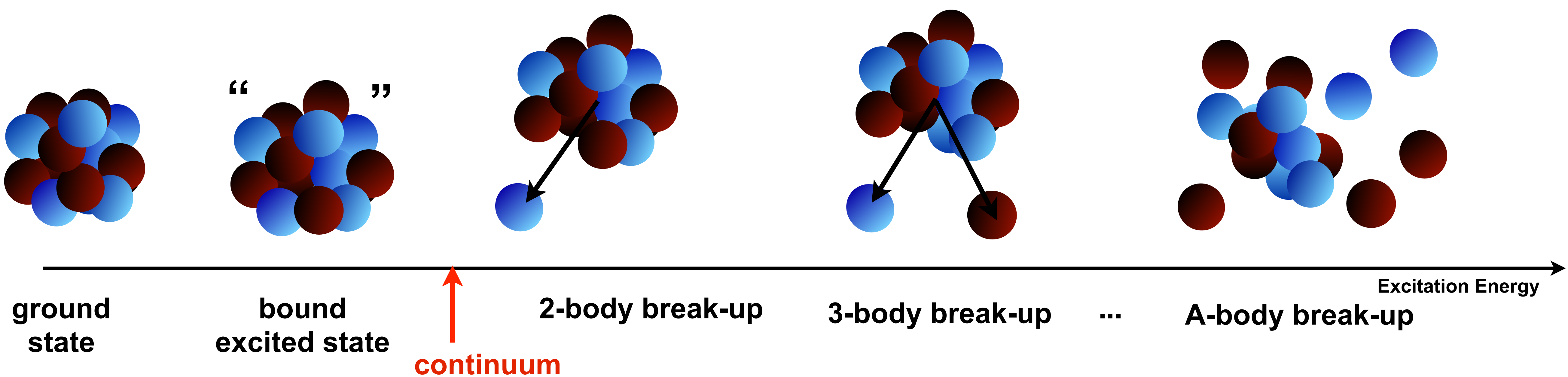

Integral Transforms

$$R(\omega, q) = \sum\!\!\!\!\!\!\int_f |\langle\Psi_f|\Theta(q)|\Psi_0\rangle|^2 \delta(\omega - E_f + E_0)$$

Exact knowledge limited in energy and mass number

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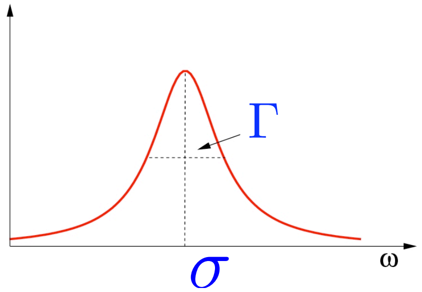
Lorentz Integral Transform

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

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



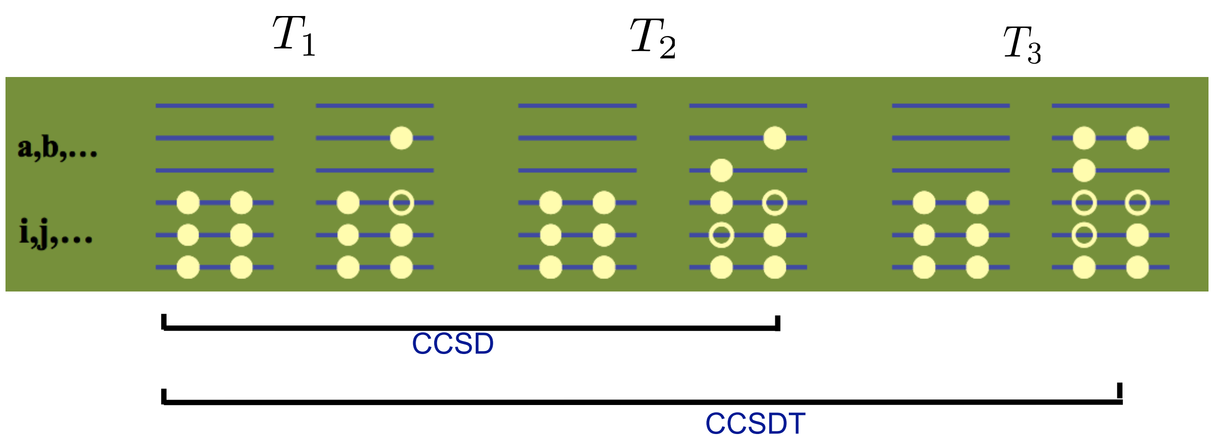
$$(H-E_0-\sigma+i\Gamma)\,|\,\tilde{\psi}\rangle=\Theta\,|\,\psi_0\rangle$$

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

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



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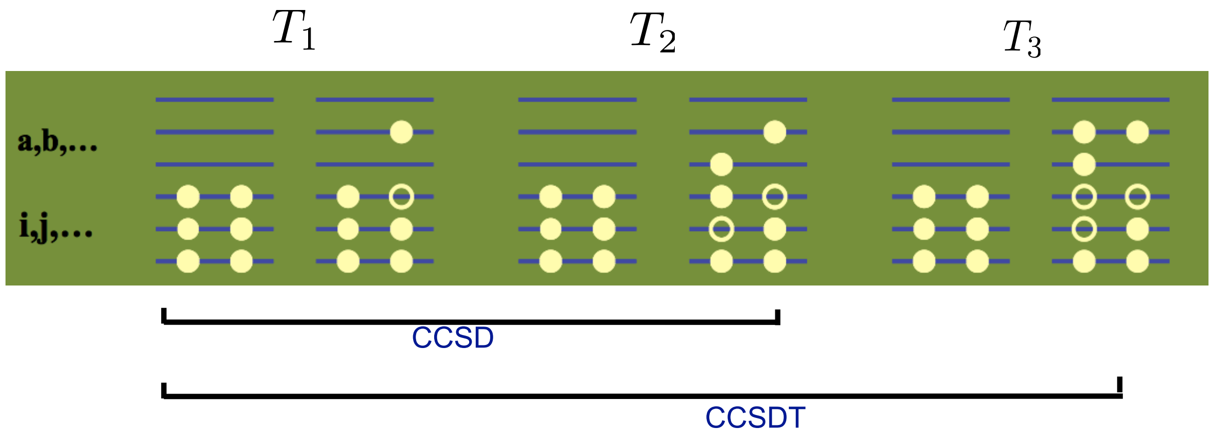

SB *et al.*, Phys. Rev. Lett. **111**, 122502 (2013)

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

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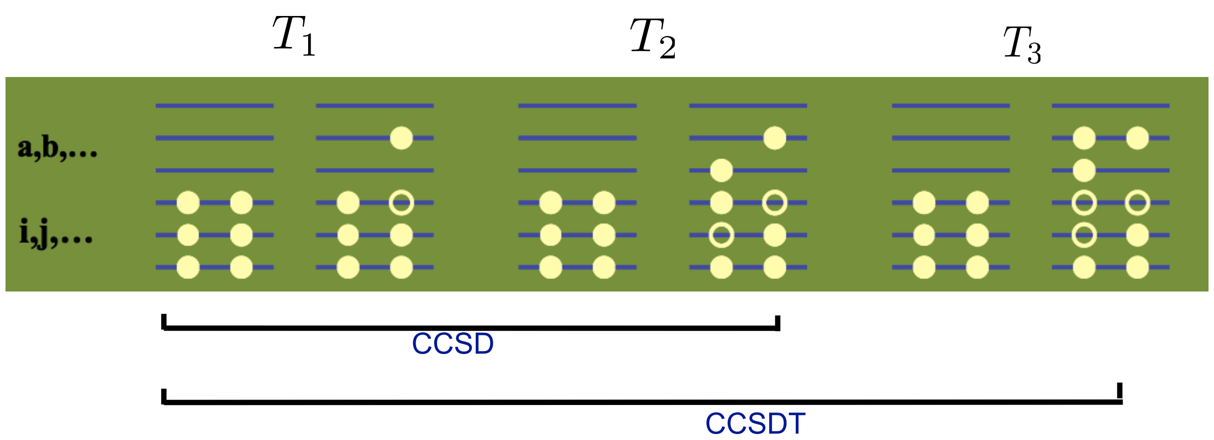

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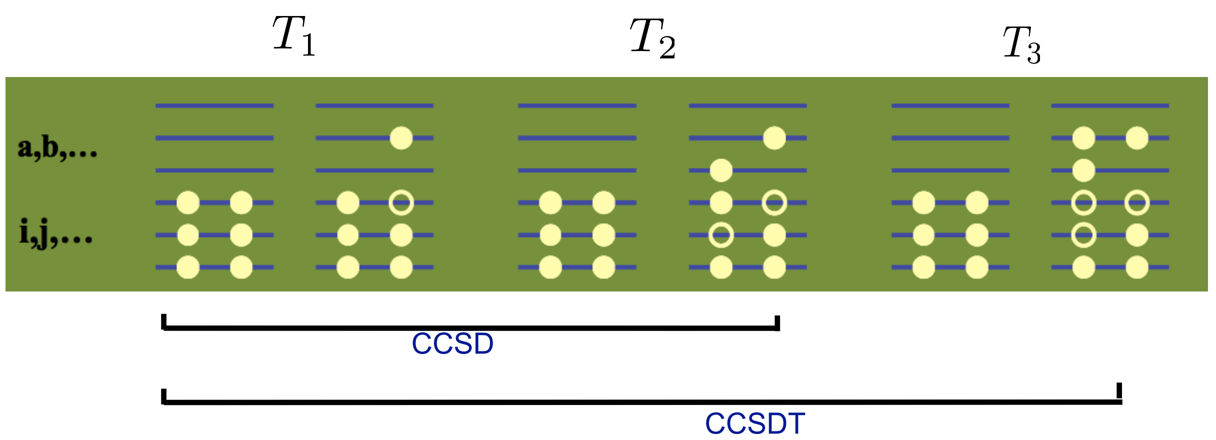

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Results with implementation at CCSD level

$$T = T_1 + T_2$$

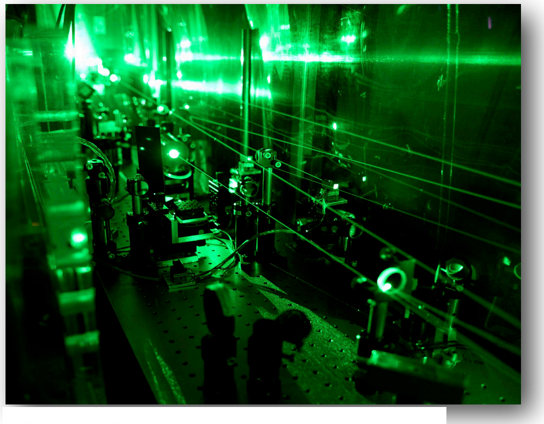
$$R = R_0 + R_1 + R_2$$

Why are EW reactions relevant?

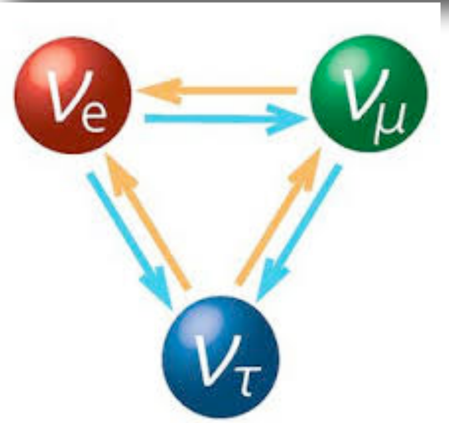
Connect to other fields of physics, where nuclear physics plays a crucial role:

- Astrophysics

- Atomic physics



- Particle physics



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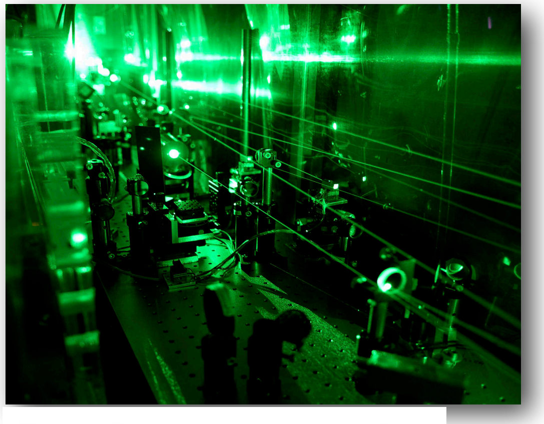

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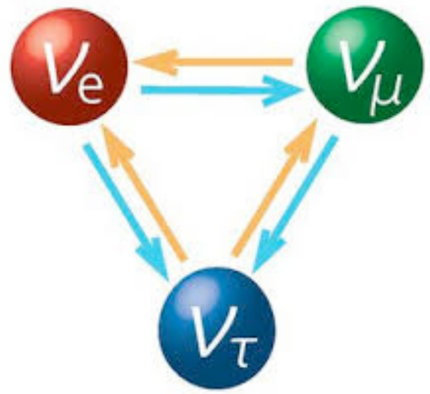
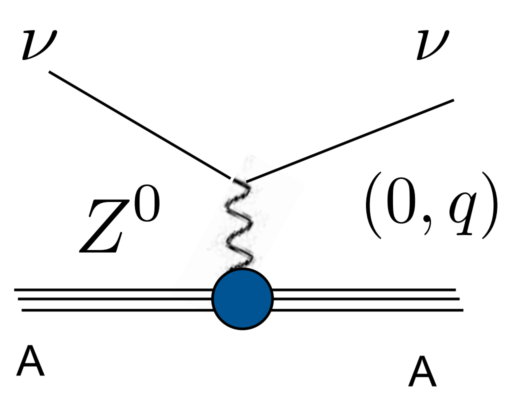


Title Text

Neutrino physics

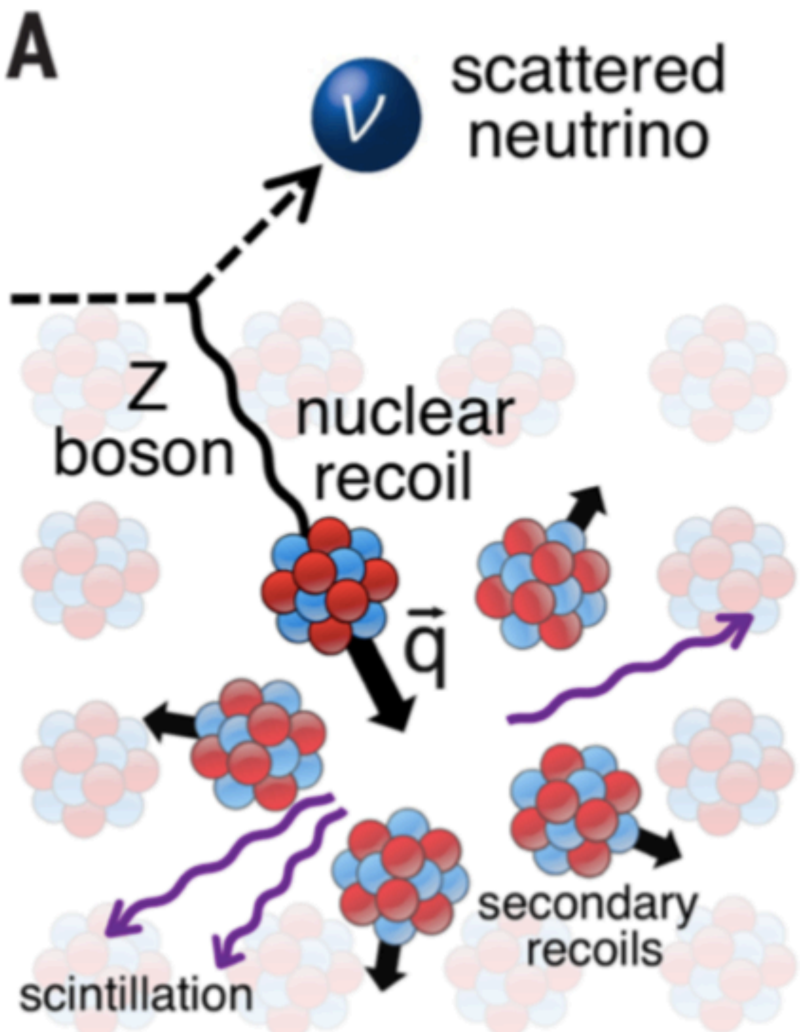
CEvNS

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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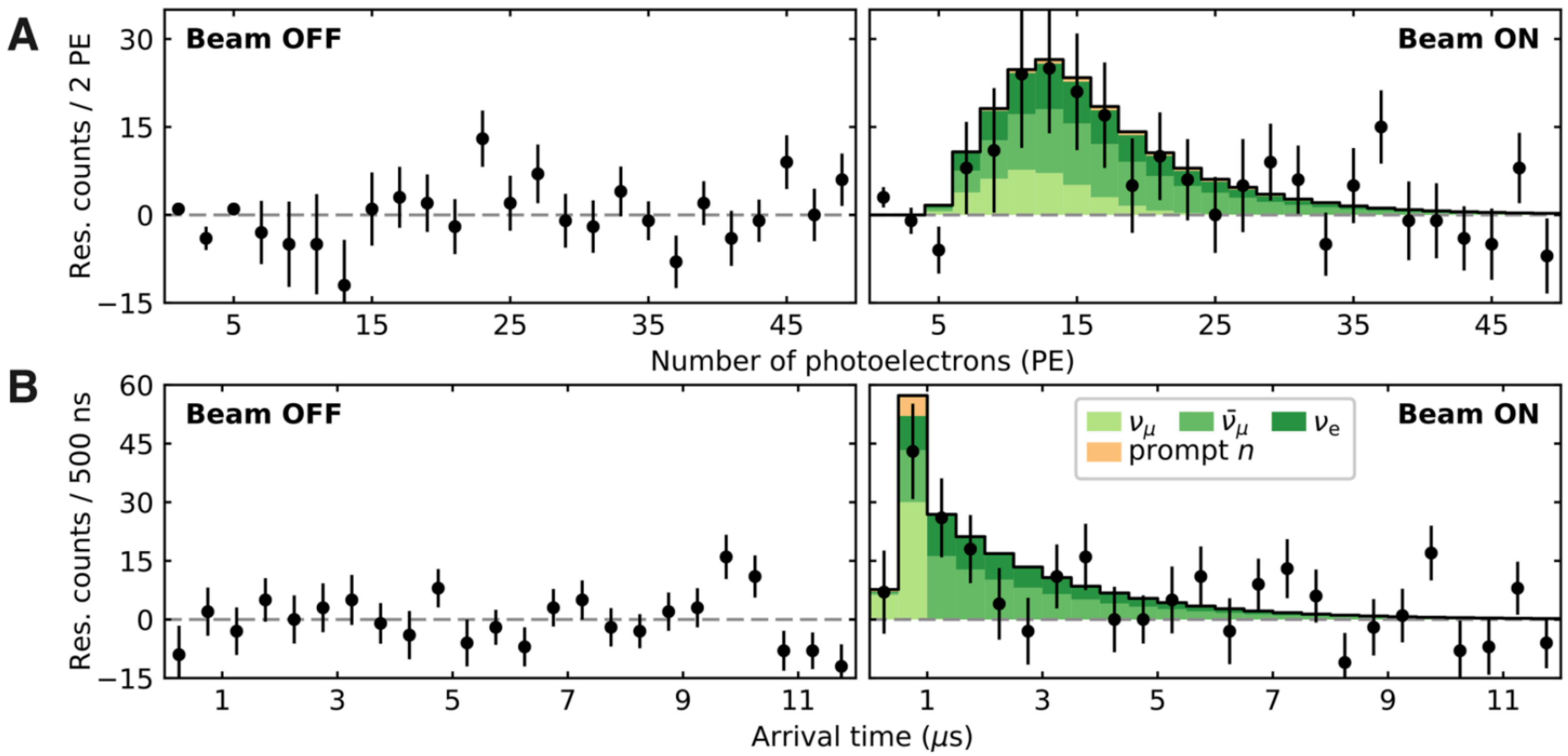
Science REPORTS

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

Observation of coherent elastic neutrino-nucleus scattering



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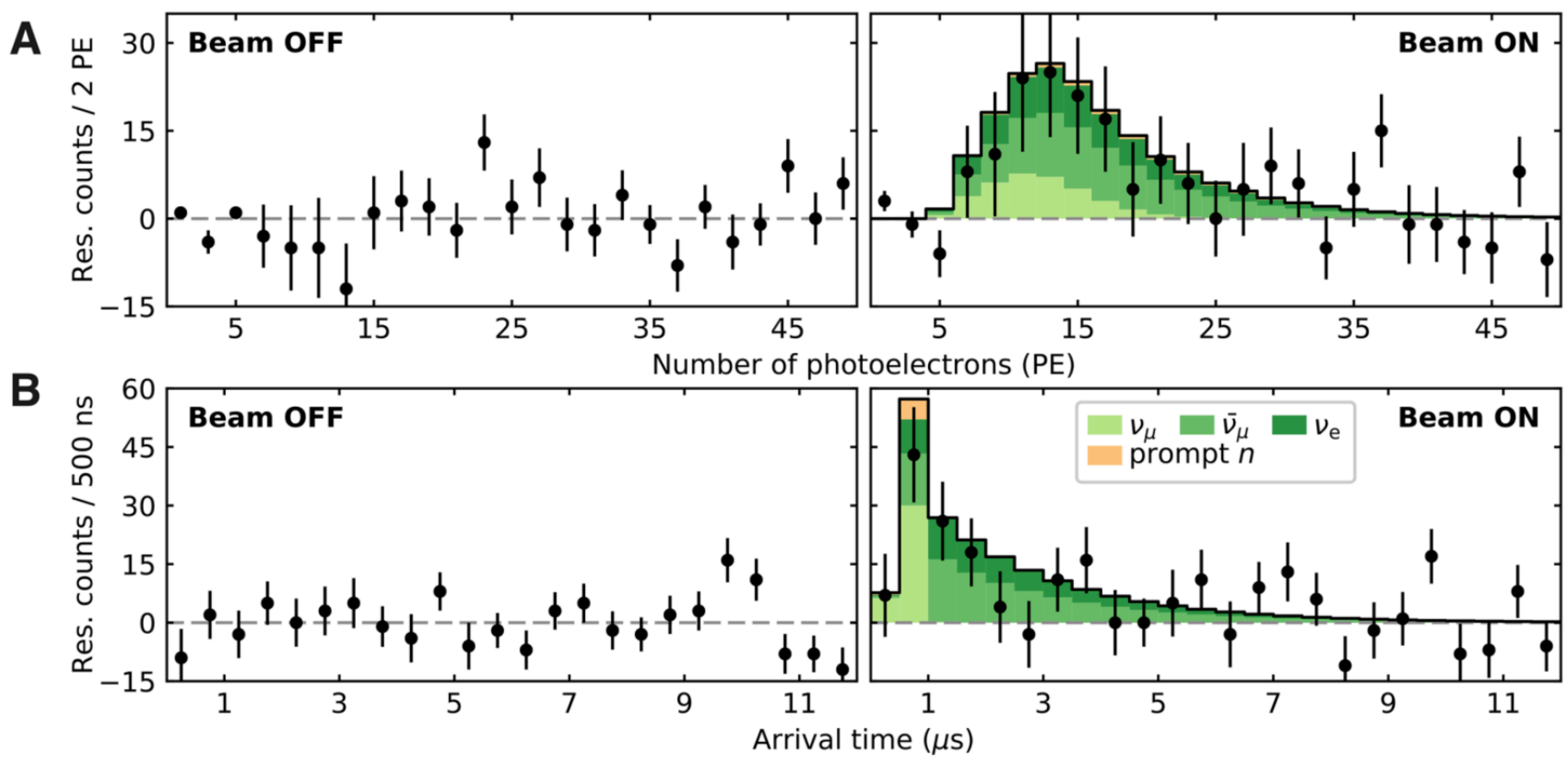
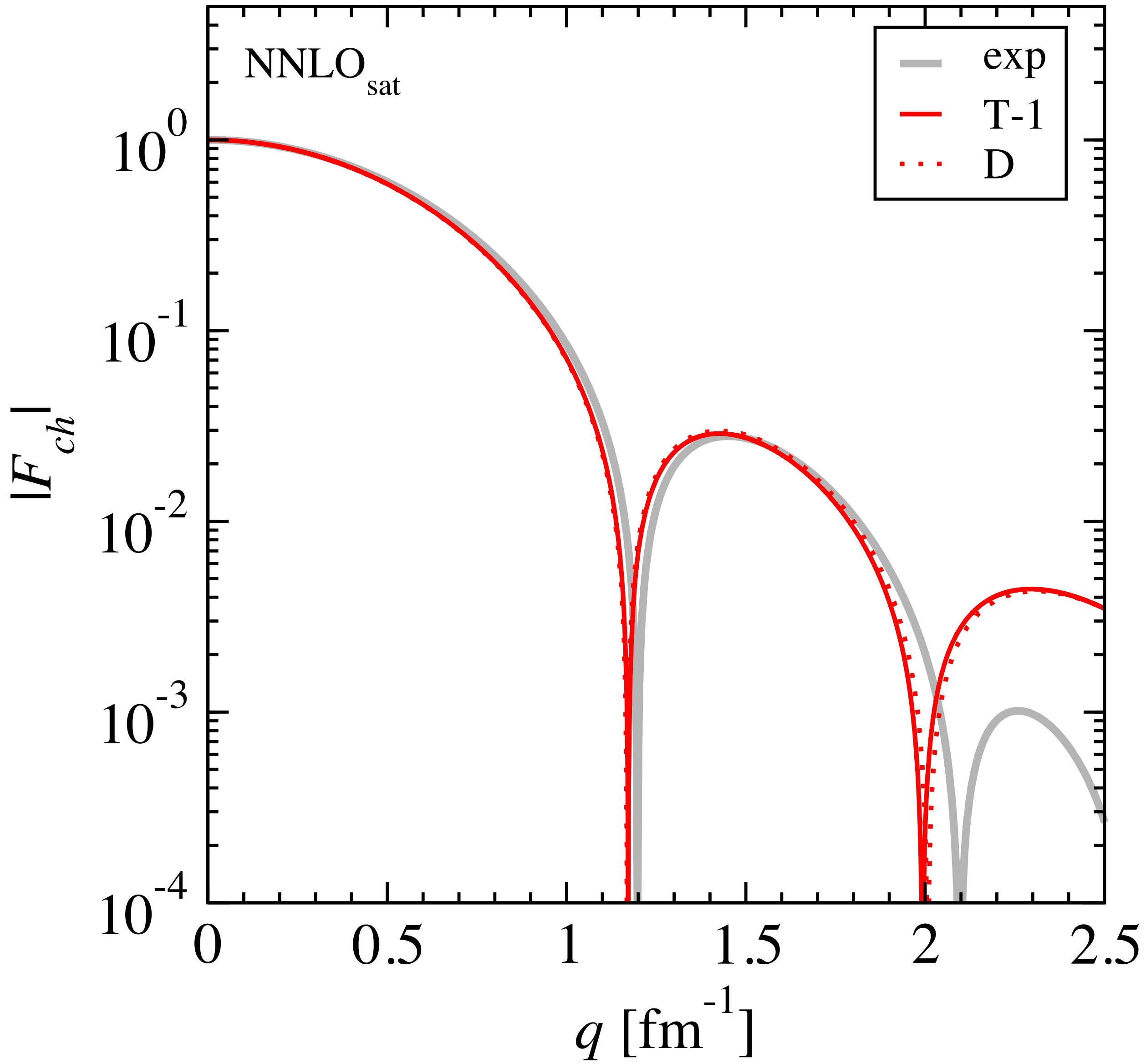


$$\frac{d\sigma}{dT}(E_\nu, T) \simeq \frac{G_F^2}{4\pi} M \left[1 - \frac{MT}{2E_\nu^2}\right] Q_W^2 F_W^2(q^2) \propto N^2 \qquad Q_W = N - (1 - 4\sin^2\theta_W) Z$$

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

^{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)

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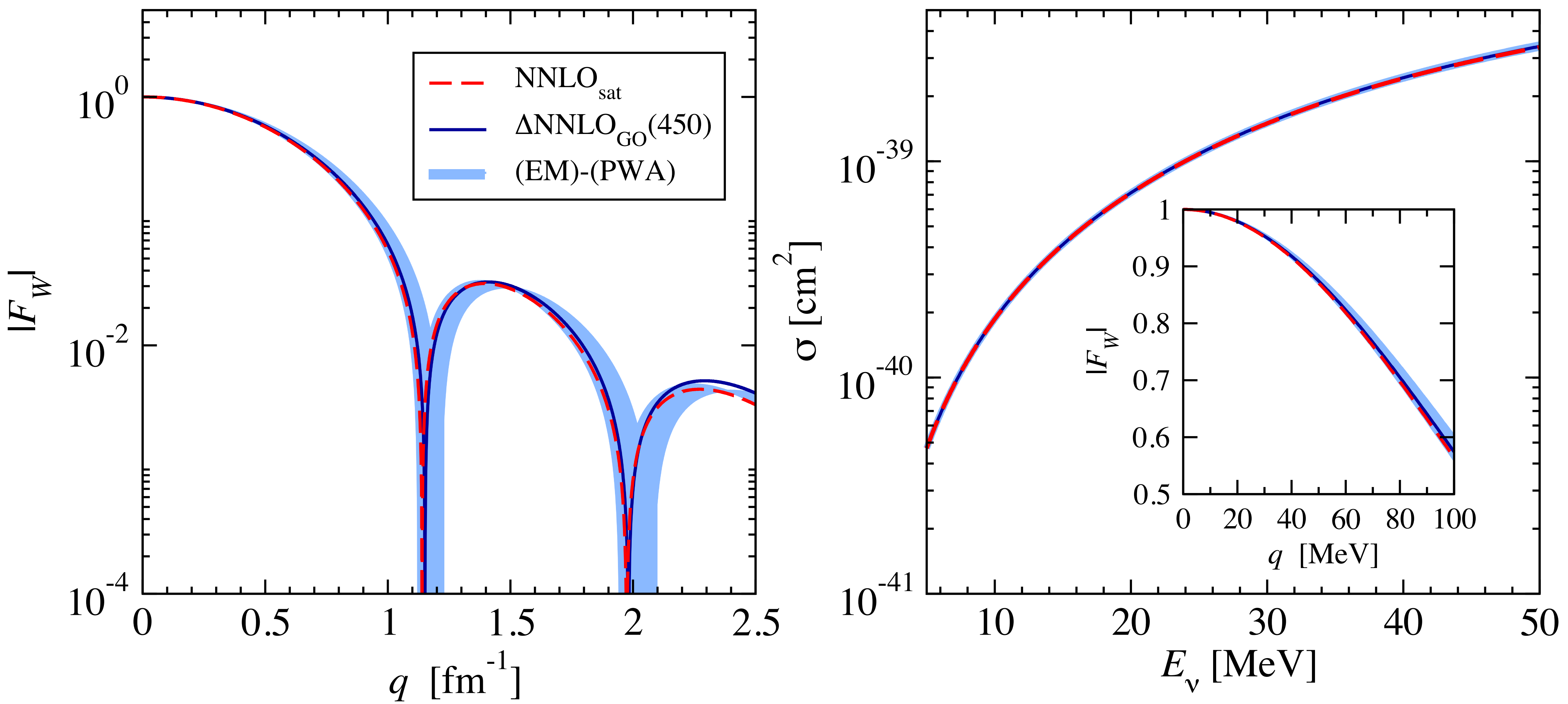
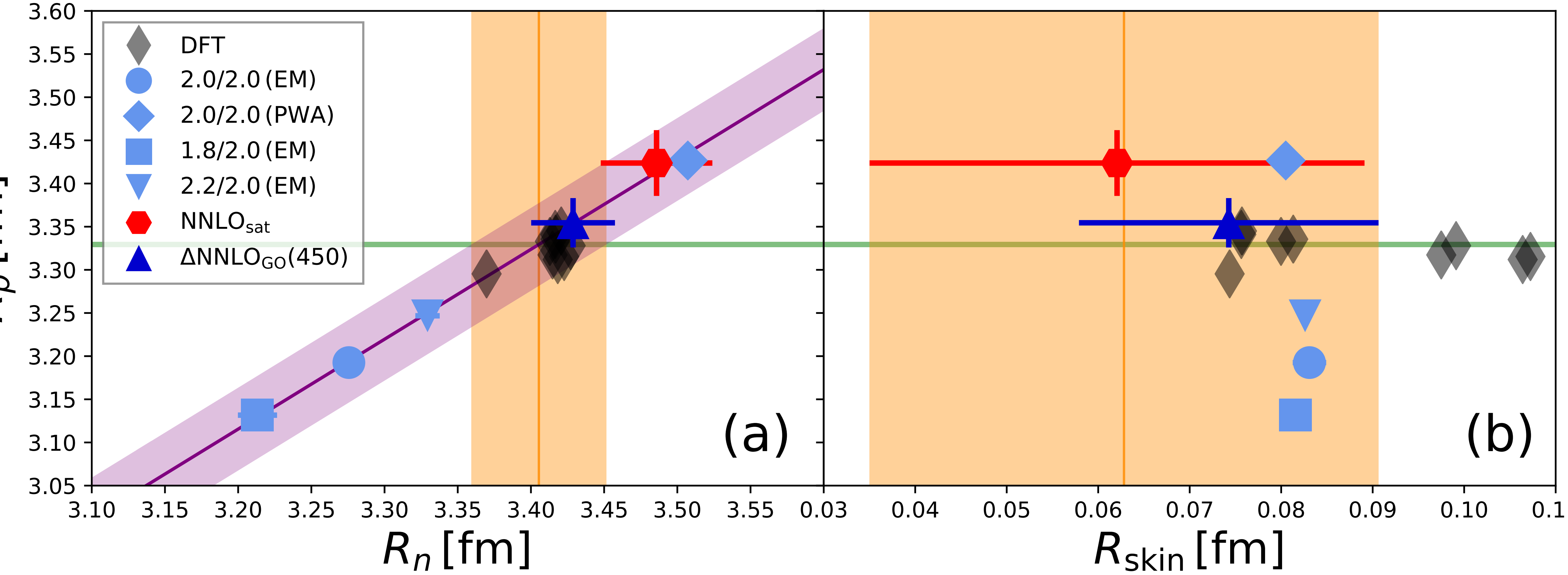


Small nuclear structure uncertainty in the cross section: 2% at q=50 MeV, as opposed to 40% estimated in Sierra et al., arXiv:1902.07398v1, later corrected to 5%, JHEP 1906:141 (2019).

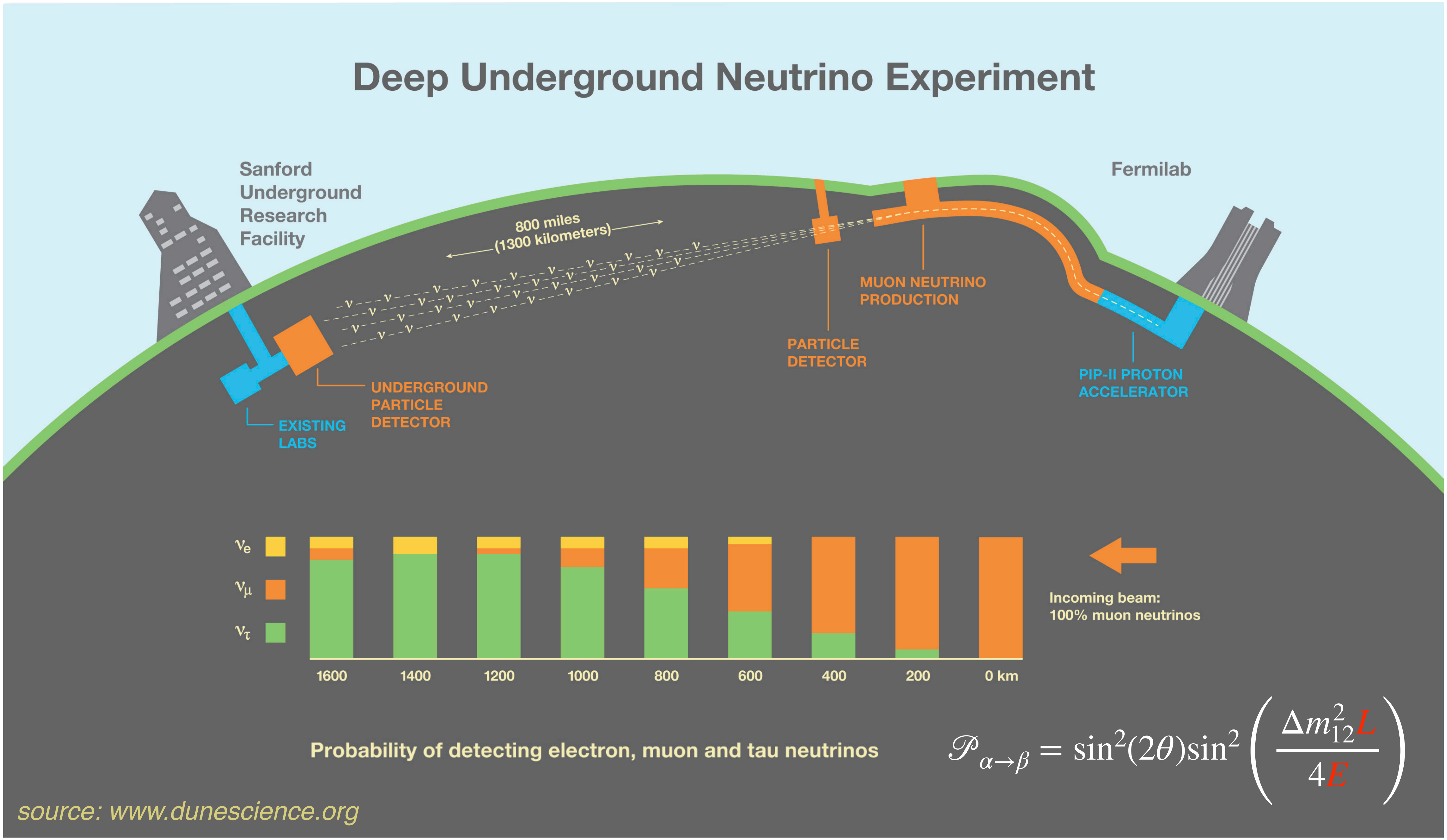
^{40}Ar neutron radius and skin-thickness

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



DFT from N. Schunk, private communication, **HFB9, SKI3, SKM*, SKO, SKX, SLY4, SLY5, UNEDF0, UNEDF1**

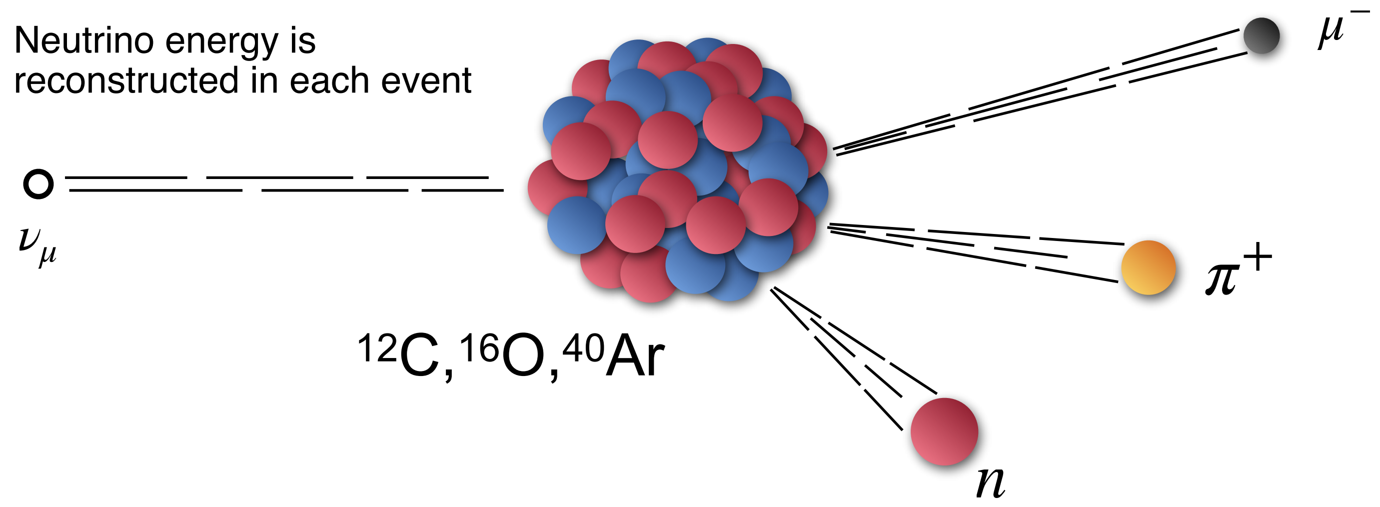
Neutrino Oscillations



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

source: www.dunescience.org

Aims and challenges



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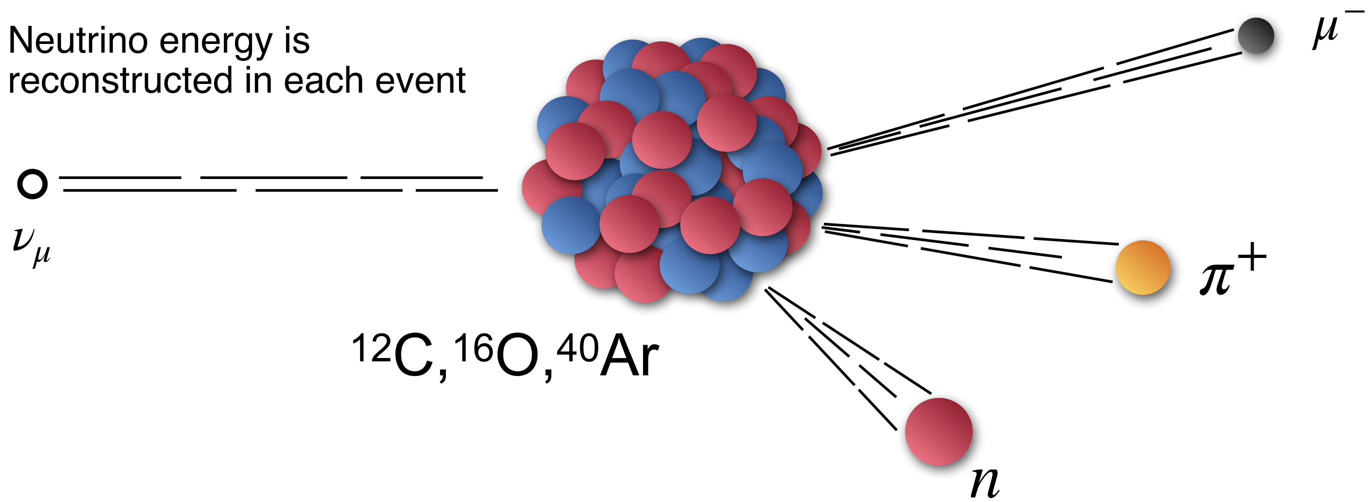

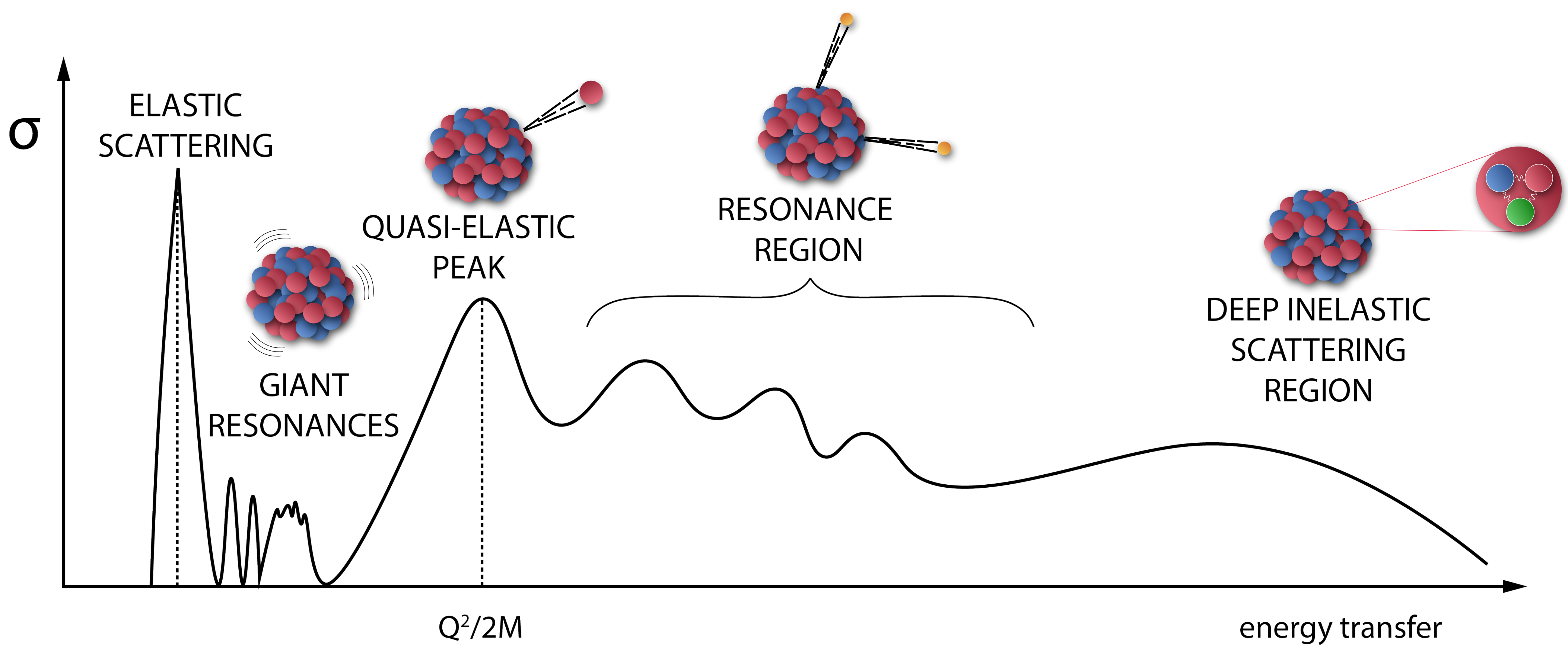

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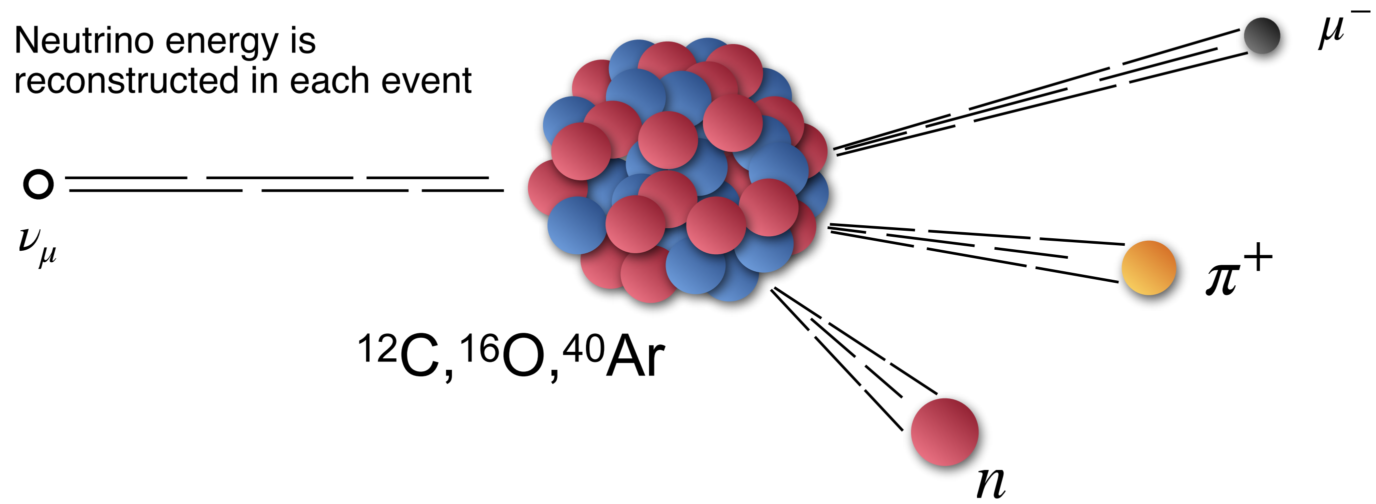

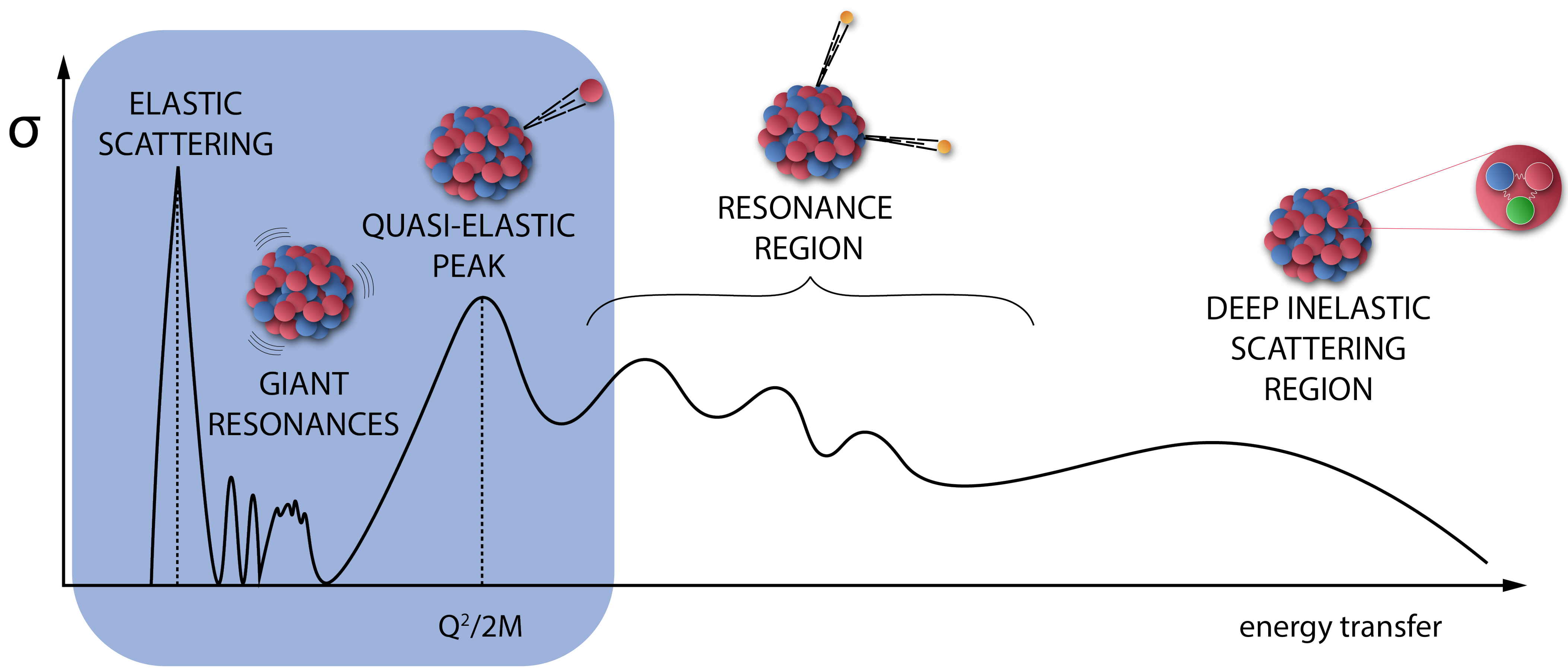

Electrons and neutrinos

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

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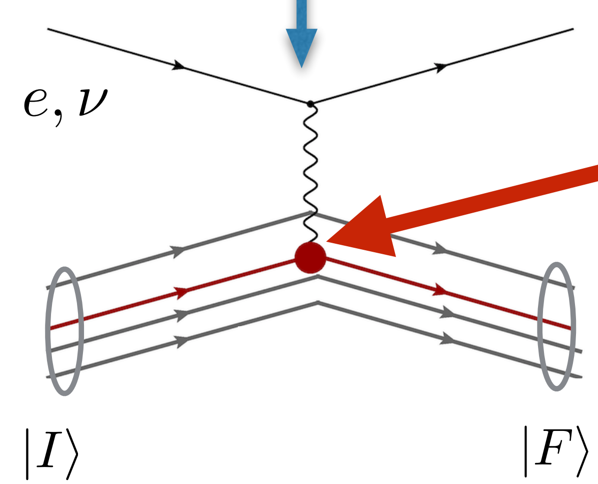
Response function
$$R_{\alpha\beta}(q,\omega) = \sum_F \langle I|j_\alpha(q,\omega)|F\rangle\langle F|j_\beta(q,\omega)|I\rangle\delta(\omega + E_I - E_F)$$



$F_A(q), F_{E/M}(q)$

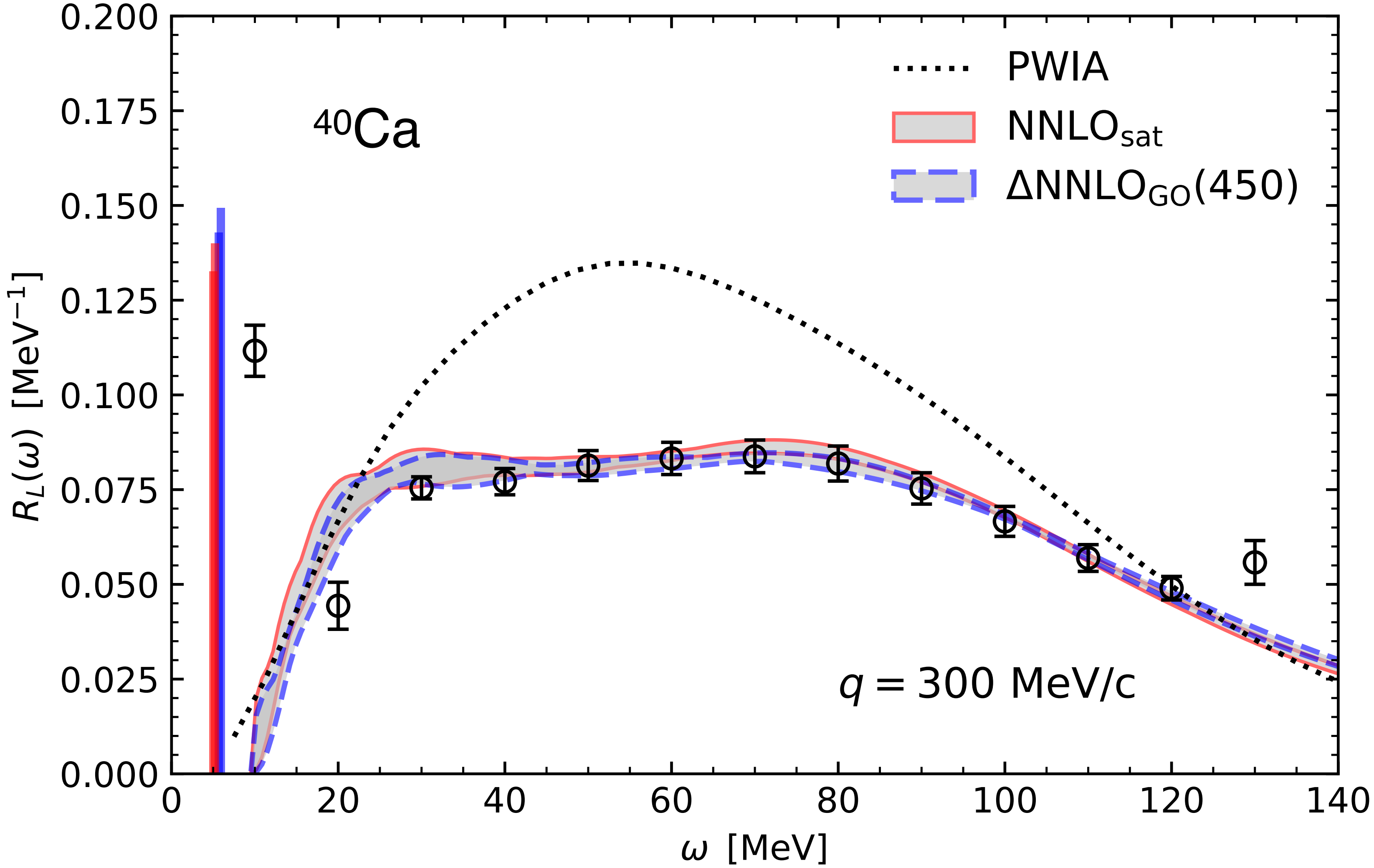
Many-nucleon dynamics
(Ab initio nuclear theory)

Single-nucleon dynamics
(lattice QCD)

Recent Highlights on e,e’

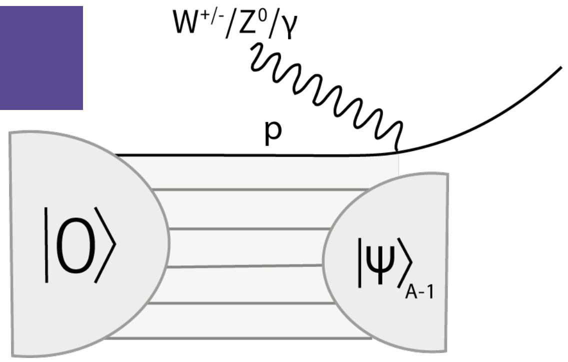
First ab-initio results for many-body system of 40 nucleons

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

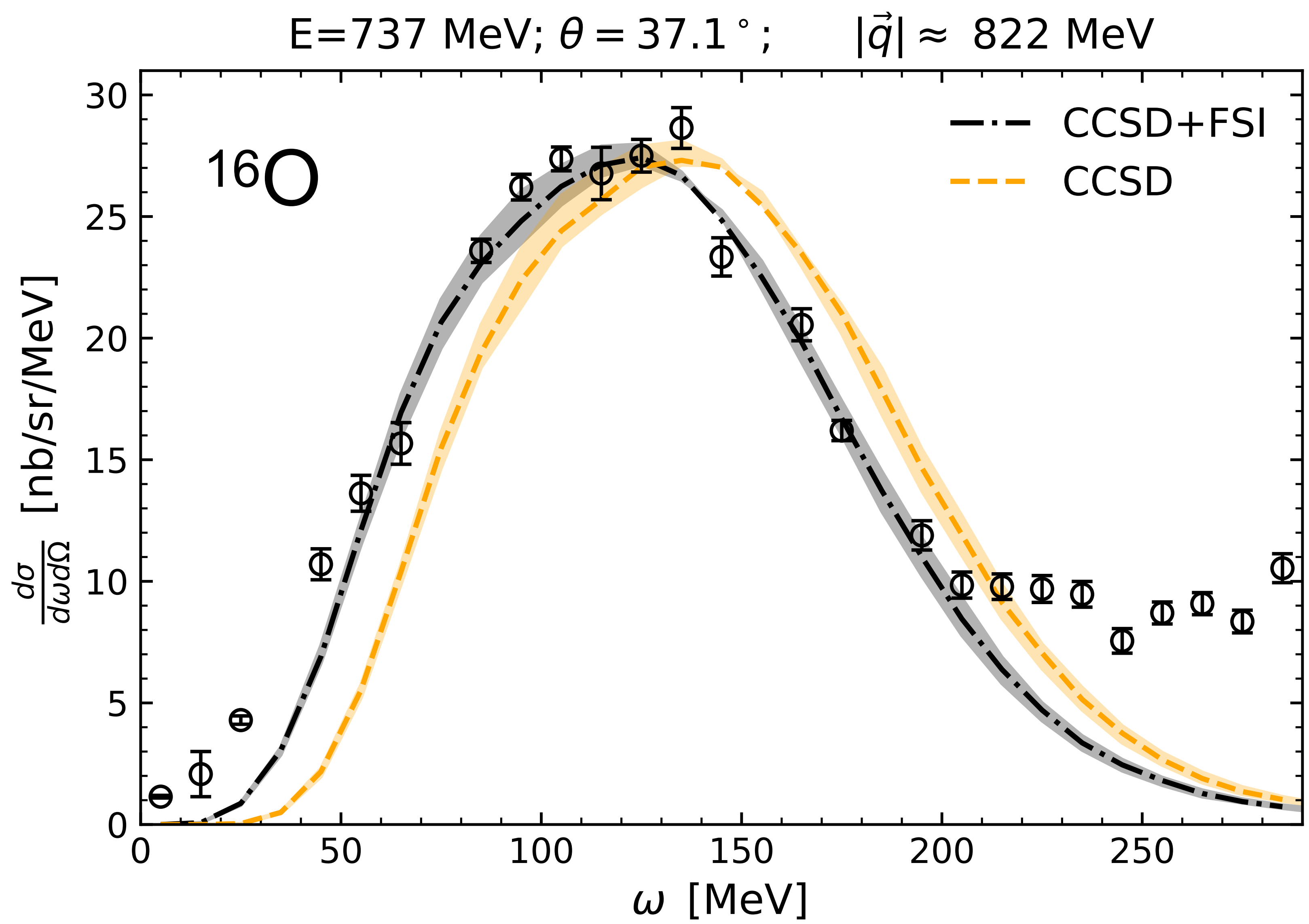


Recent Highlights on e,e'

Access higher energies with Spectral Functions



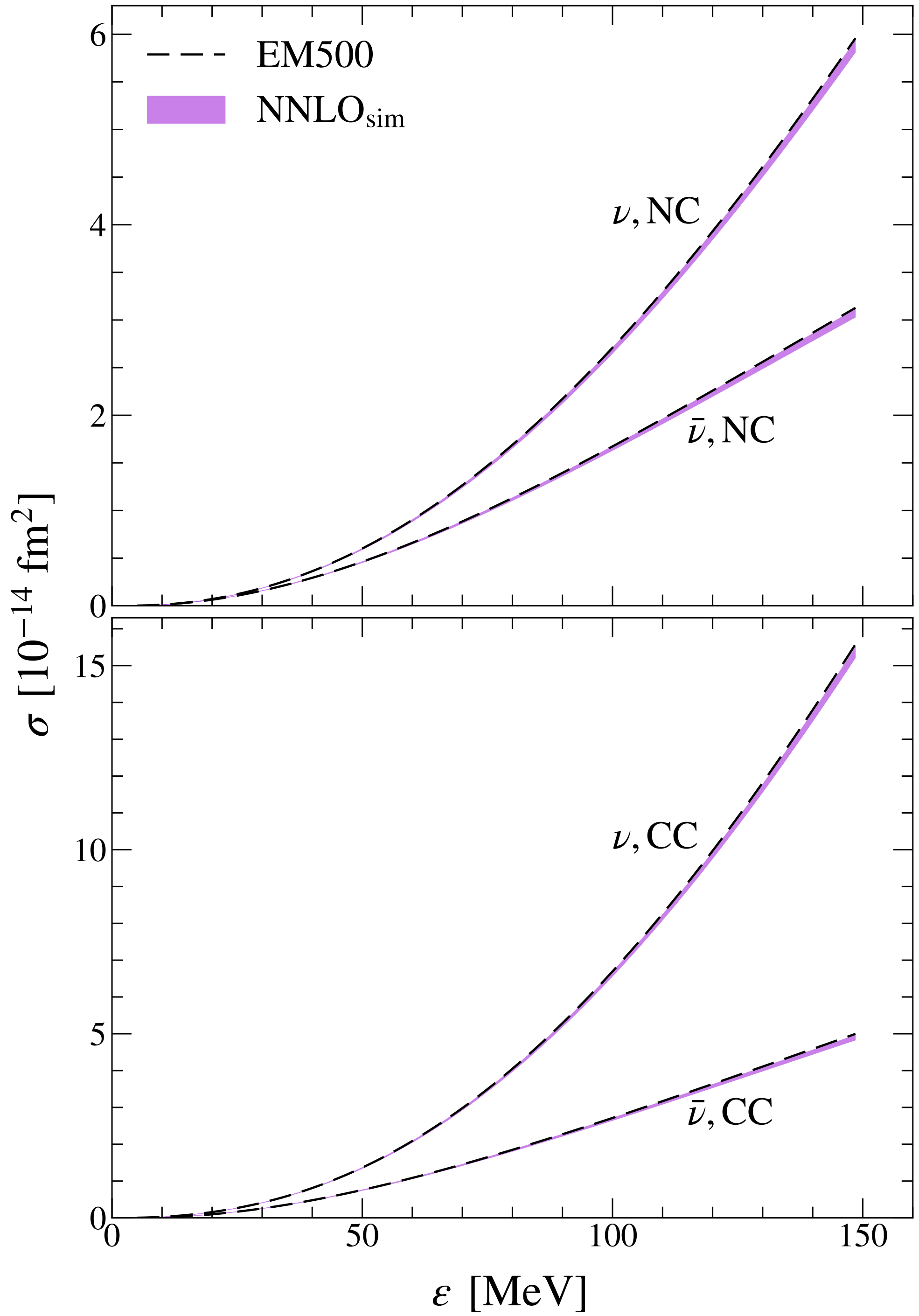
Sobcyzk, Bacca, to be submitted (2022)

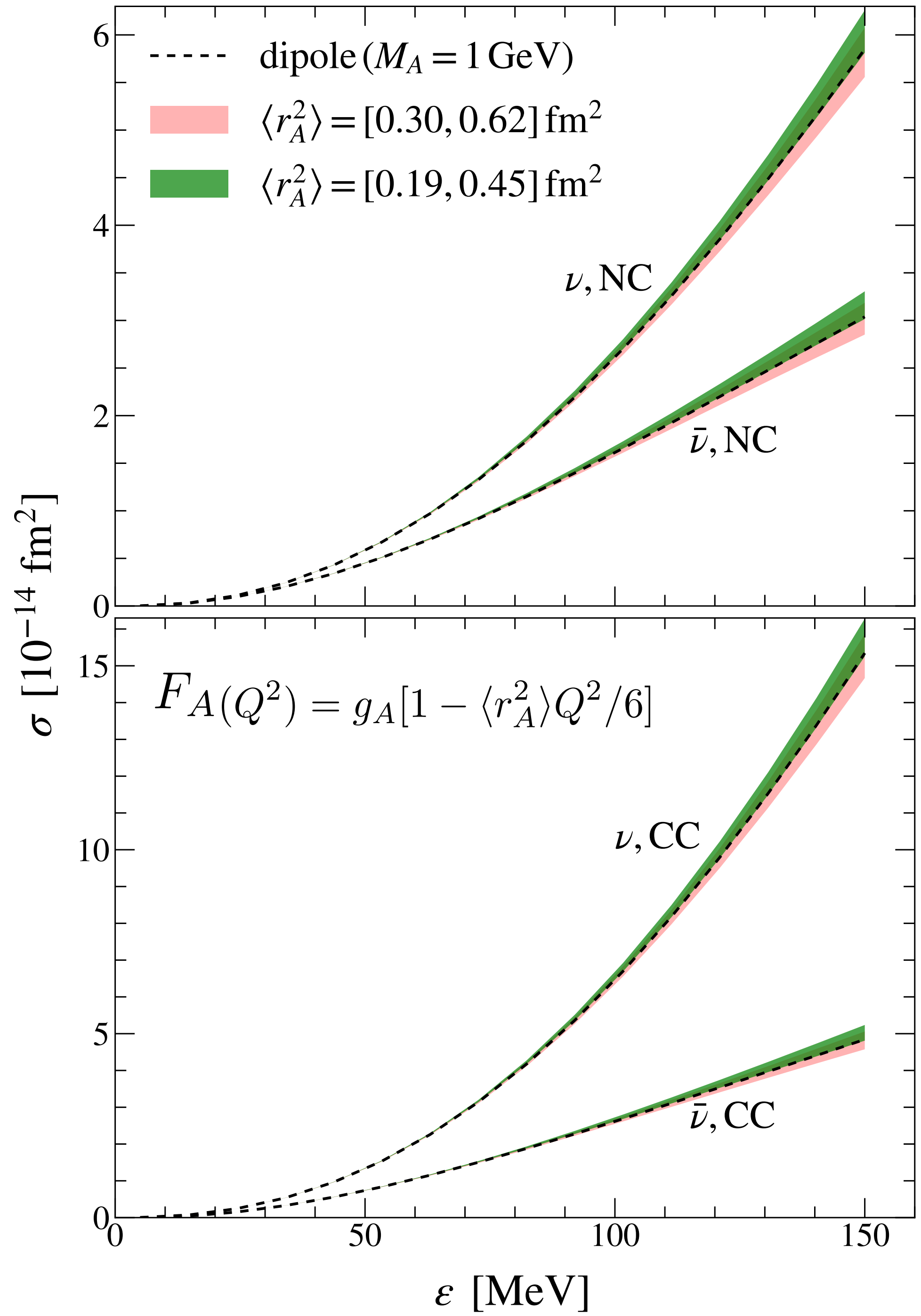


(Anti)neutrino-deuteron scattering

B. Acharya and SB, PRC **101**, 015505 (2020)

$j_\alpha(q,\omega)$ within chiral EFT





Outlook

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- 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**

Thanks for your attention!

Backup

Inversion of the LIT

The inversion is performed numerically with a regularization procedure needed for the solution of an ill-posed problem

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

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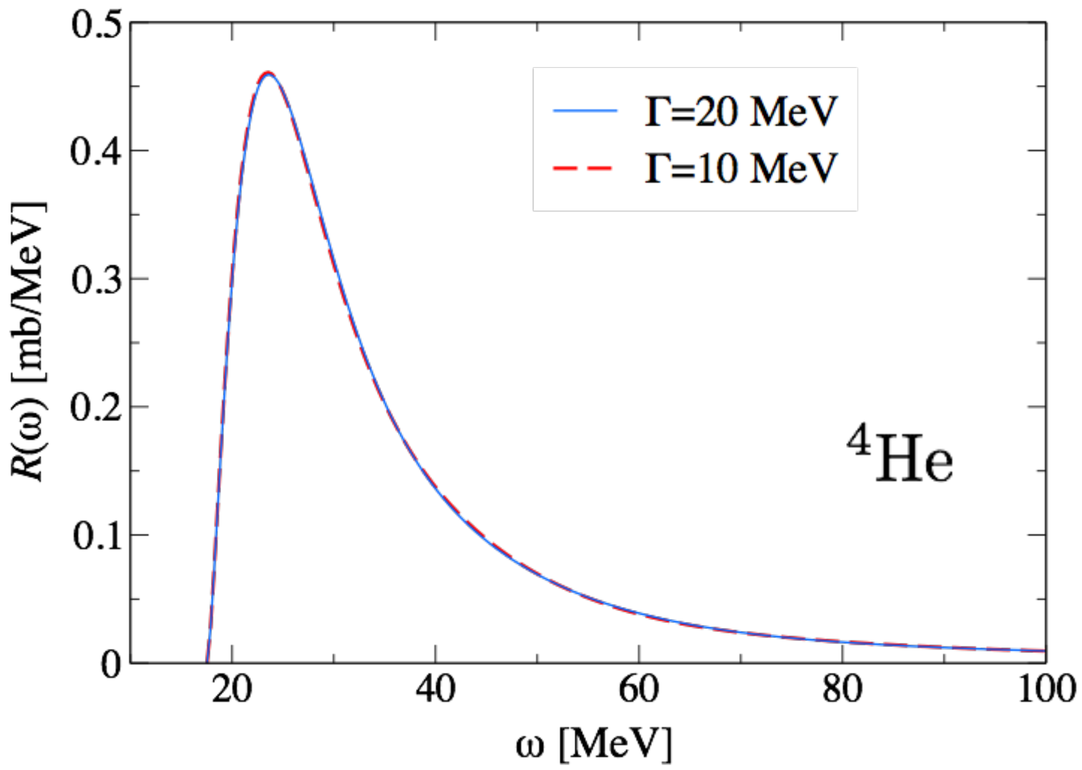
Least square fit of the coefficients c_i to reconstruct the response function



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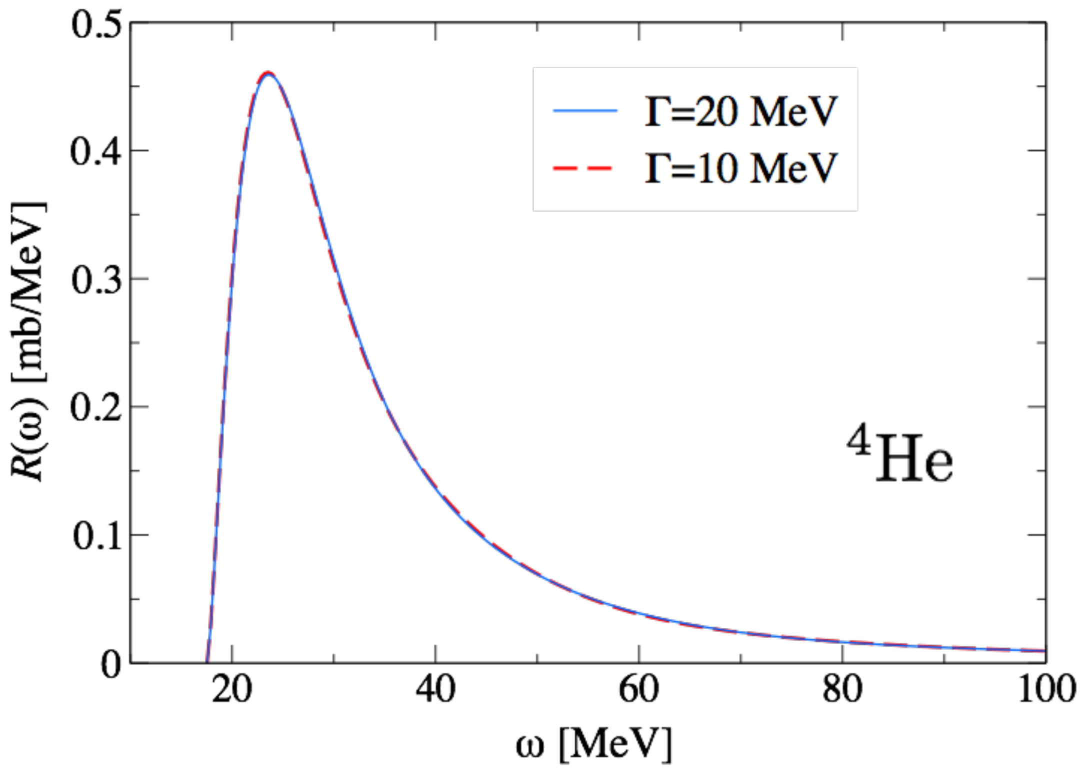
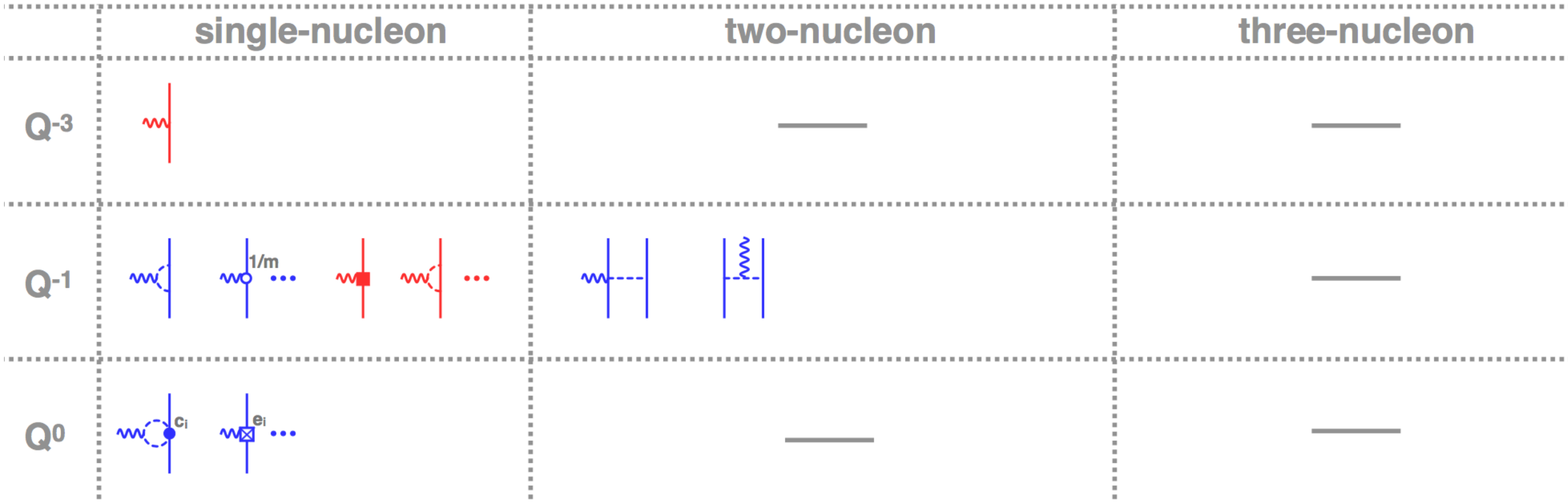


Message: using bound-states techniques to calculate the LIT is correct and inversions are stable If the LIT is calculated precisely enough

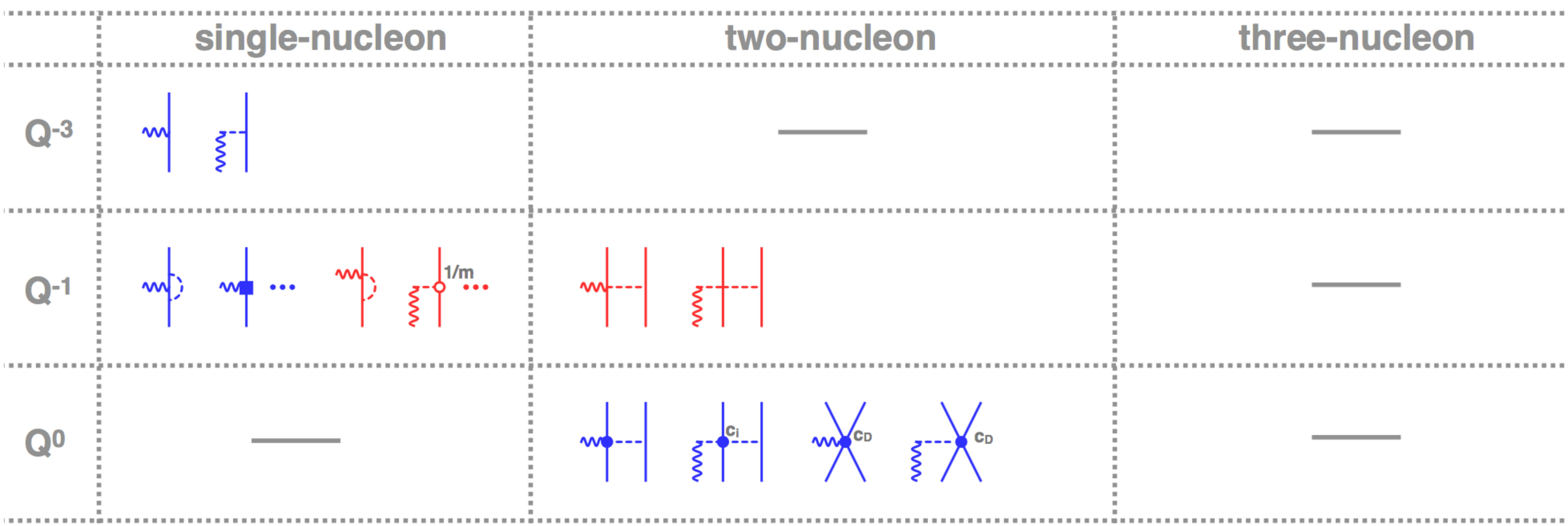
Deuteron neutrino-nucleus scattering

From E.Epelbaum, Mainz Workshop, October 2018

Chiral expansion of the electromagnetic **current** and **charge** operators



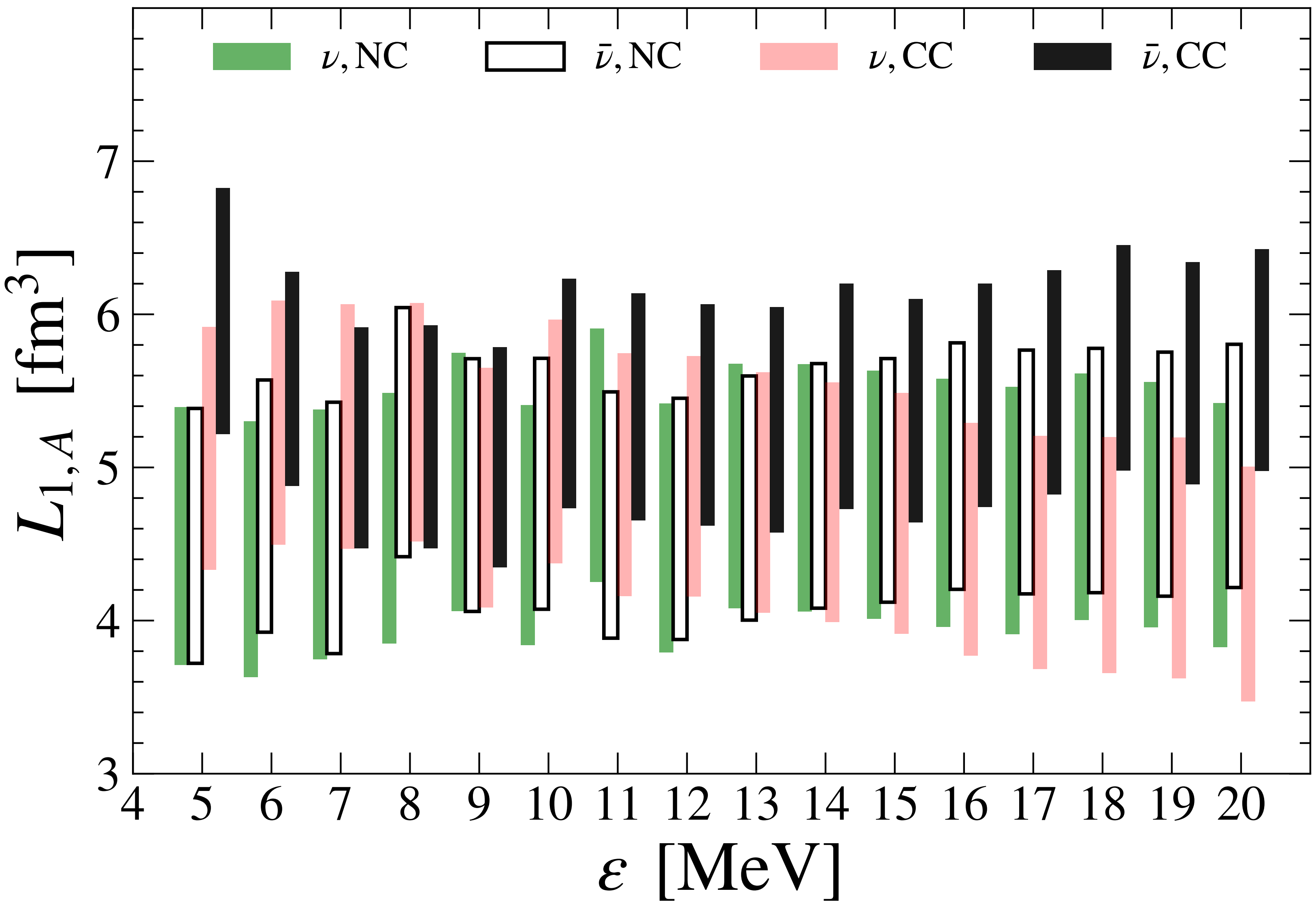
Chiral expansion of the axial **current** and **charge** operators



(Anti)neutrino-deuteron scattering

B. Acharya and SB, PRC 101, 015505 (2020)

$$\sigma(\epsilon) = a(\epsilon) + L_{1,A} b(\epsilon)$$ Butler,Chen,Kong, 2001



(Anti)neutrino-deuteron scattering

B. Acharya and SB, PRC 101, 015505 (2020)