Coherent elastic neutrino scattering for ^{40}Ar from first principles

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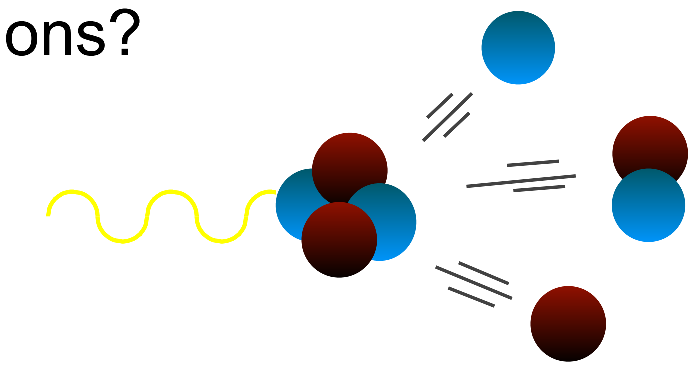
Outline

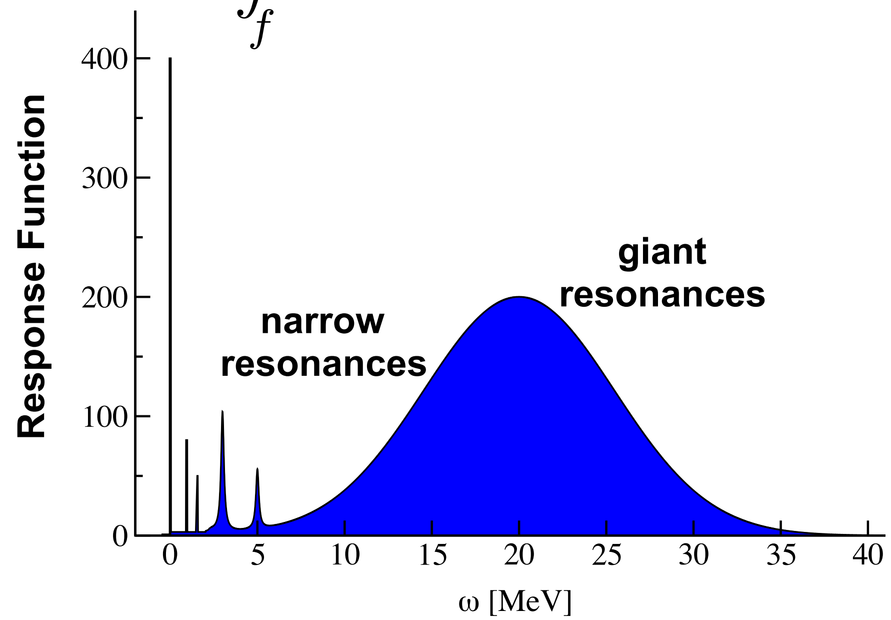
- Motivation
- The electroweak sector:
  — coherent elastic neutrino scattering
  — inelastic lepton scattering
- Outlook

Motivation

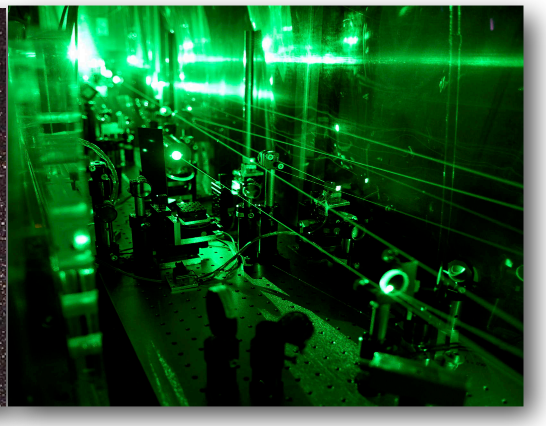
- How does the nucleus respond to external electroweak excitations?

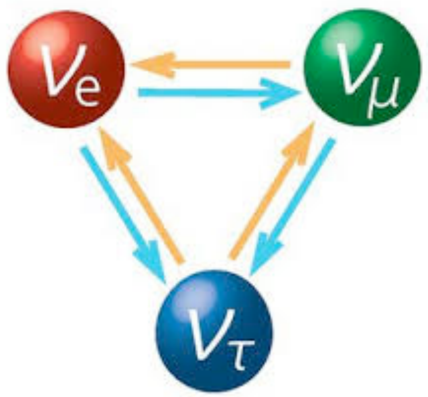


$$R(\omega, q) = \sum\!\!\!\!\!\!\int_f |\langle \Psi_f | \Theta(q) | \Psi_0 \rangle|^2 \delta(\omega - E_f + E_0)$$



- Interesting in nuclear physics and useful in other fields of physics, where nuclear physics plays a crucial role:
  - Astrophysics:
  - Atomic physics
  - Particle physics





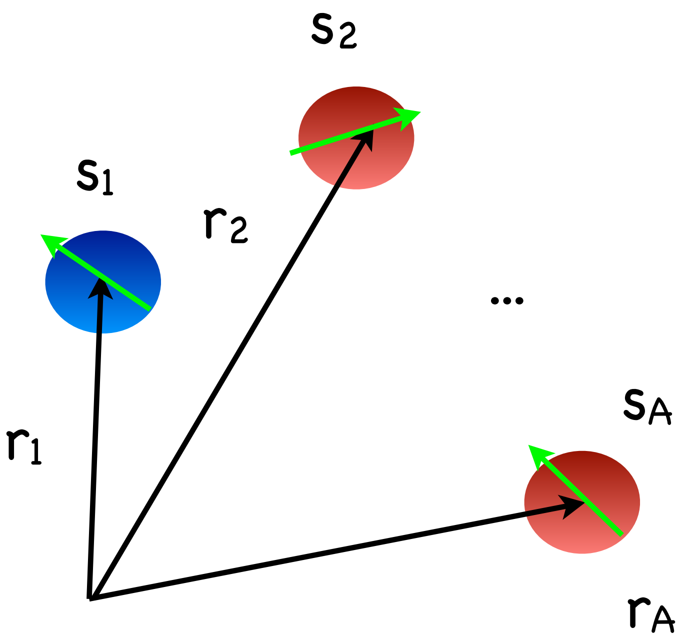
Nuclear structure theory

Several particle physics experiments that look for BSM physics use nuclei as targets. Hence, we need a solid theory to study/quantify nuclear structure effects.

Ab initio approach

- 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



$$H|\psi\rangle = E|\psi\rangle$$

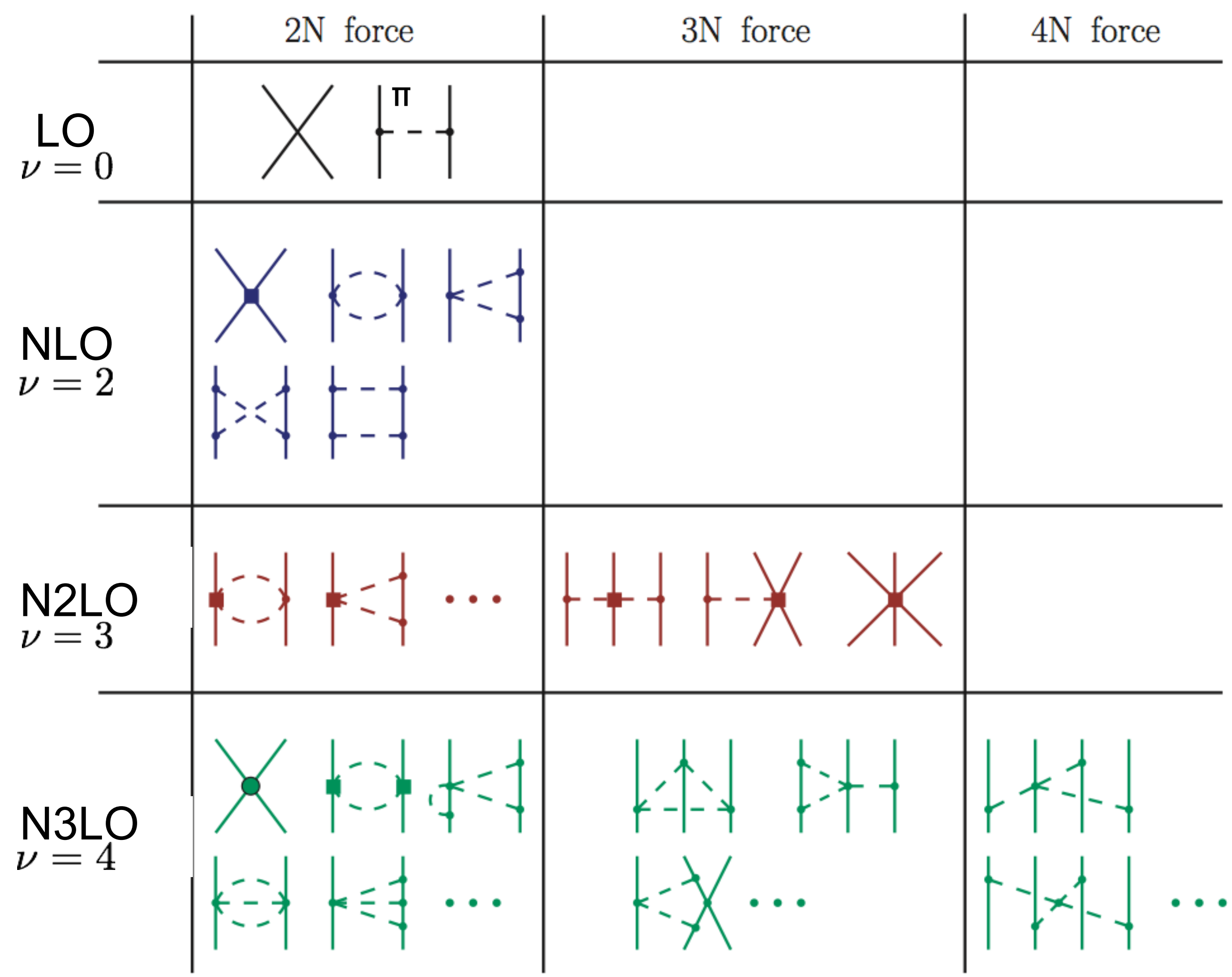
$$H = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + \dots$$

- Find numerical solutions with no approximations or controllable approximations

Nuclear structure theory

Several particle physics experiments that look for BSM physics use nuclei as targets. Hence, we need a solid theory to study/quantify nuclear structure effects.

Chiral effective field theory



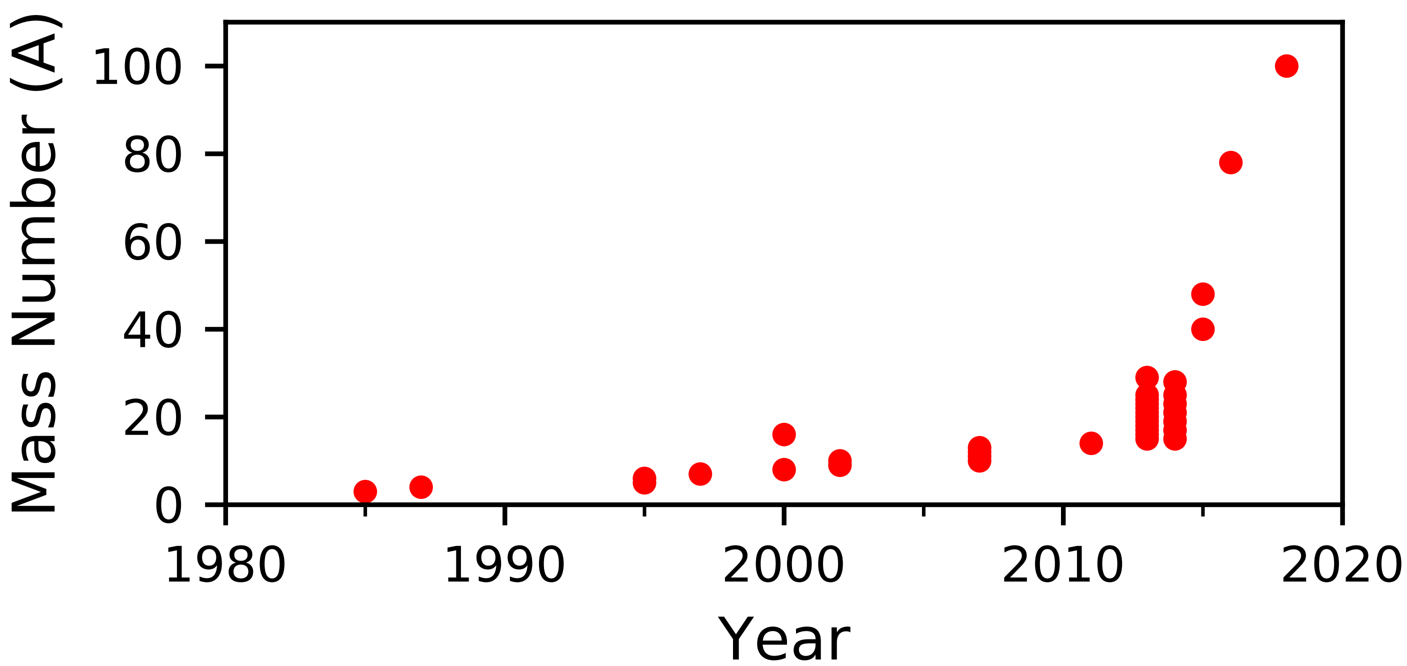
- Systematic approach (order-by-order)
- There are NN and 3NF starting from N2LO
- Low energy constants (LEC) are fit to experiment
- Once Hamiltonian has been calibrated it can be used to predict a variety of observables using a few- or many-body method

Nuclear structure theory

Several particle physics experiments that look for BSM physics use nuclei as targets. Hence, we need a solid theory to study/quantify nuclear structure effects.

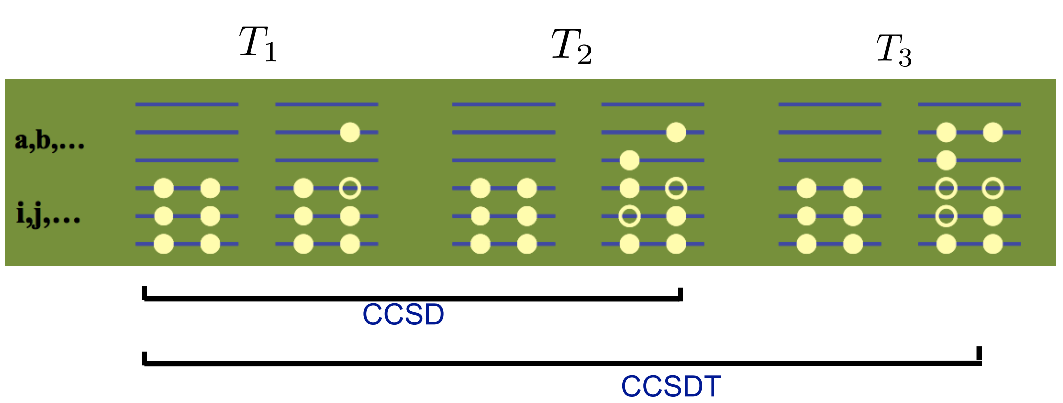
Coupled-cluster theory

In collaboration with ORNL group



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

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



$$R(\omega, q) \rightarrow \boxed{(\bar{H} - E_0 - \sigma + i\Gamma)|\tilde{\Psi}_R\rangle = \bar{\Theta}|\Phi_0\rangle}$$

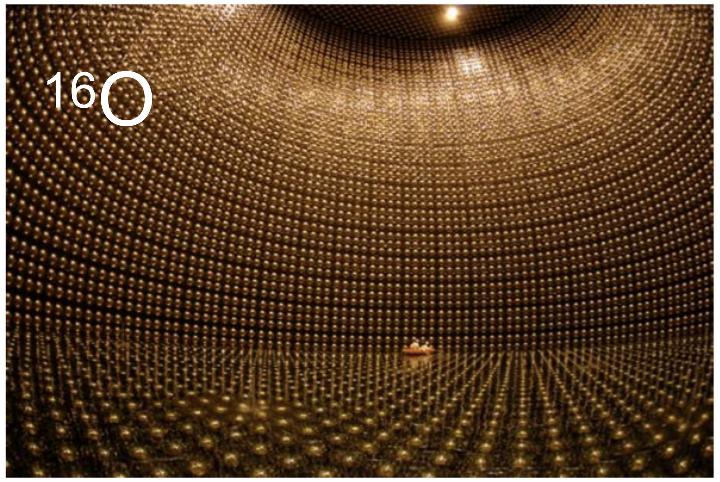
SB *et al.*,
Phys. Rev. Lett. **111**, 122502 (2013)

Electroweak sector

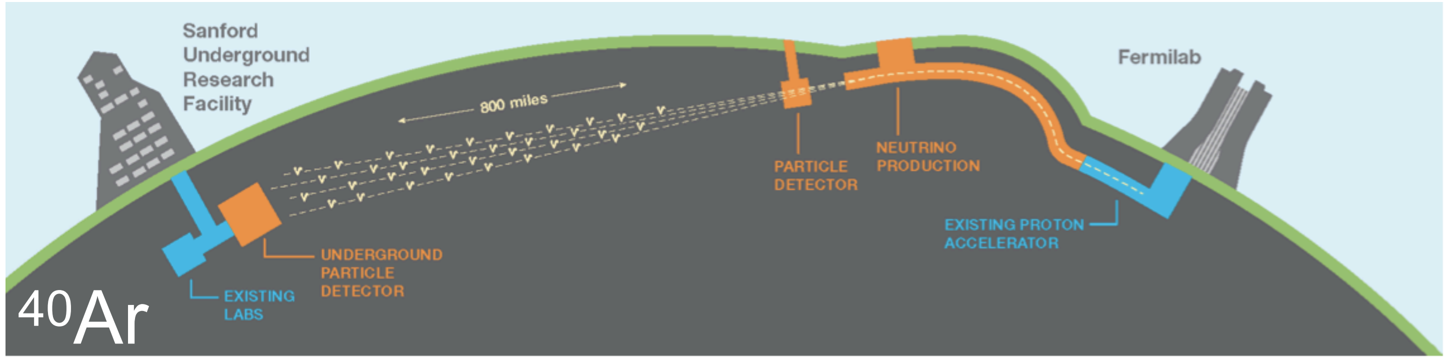
Measuring the elusive neutrinos …

Various materials including, ^{40}Ar

Short and Long-baseline neutrino experiments



T2K

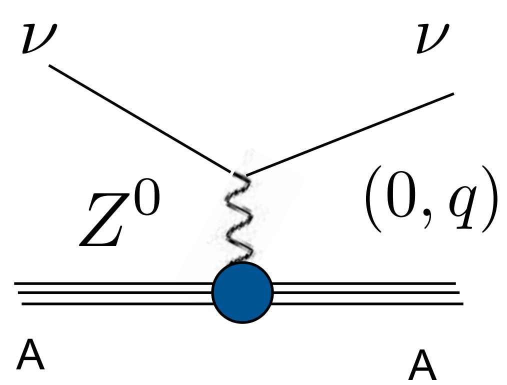


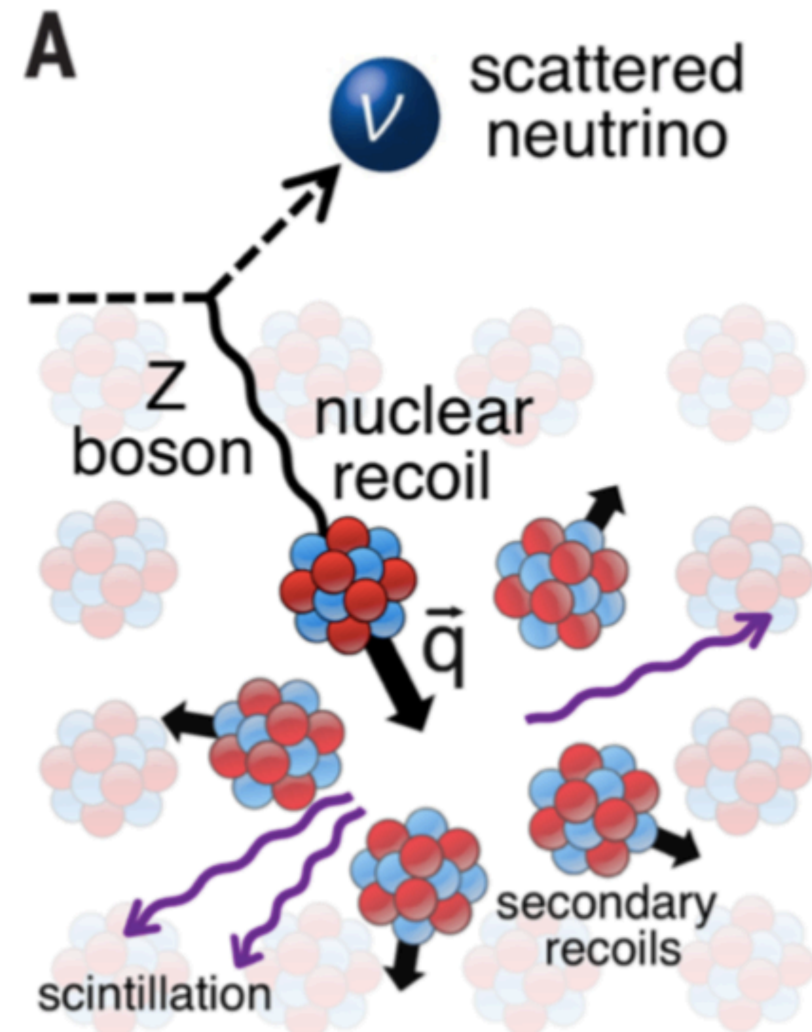
DUNE

Can ab-initio nuclear theory impact these fields?

Coherent elastic neutrino scattering

CEvNS





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

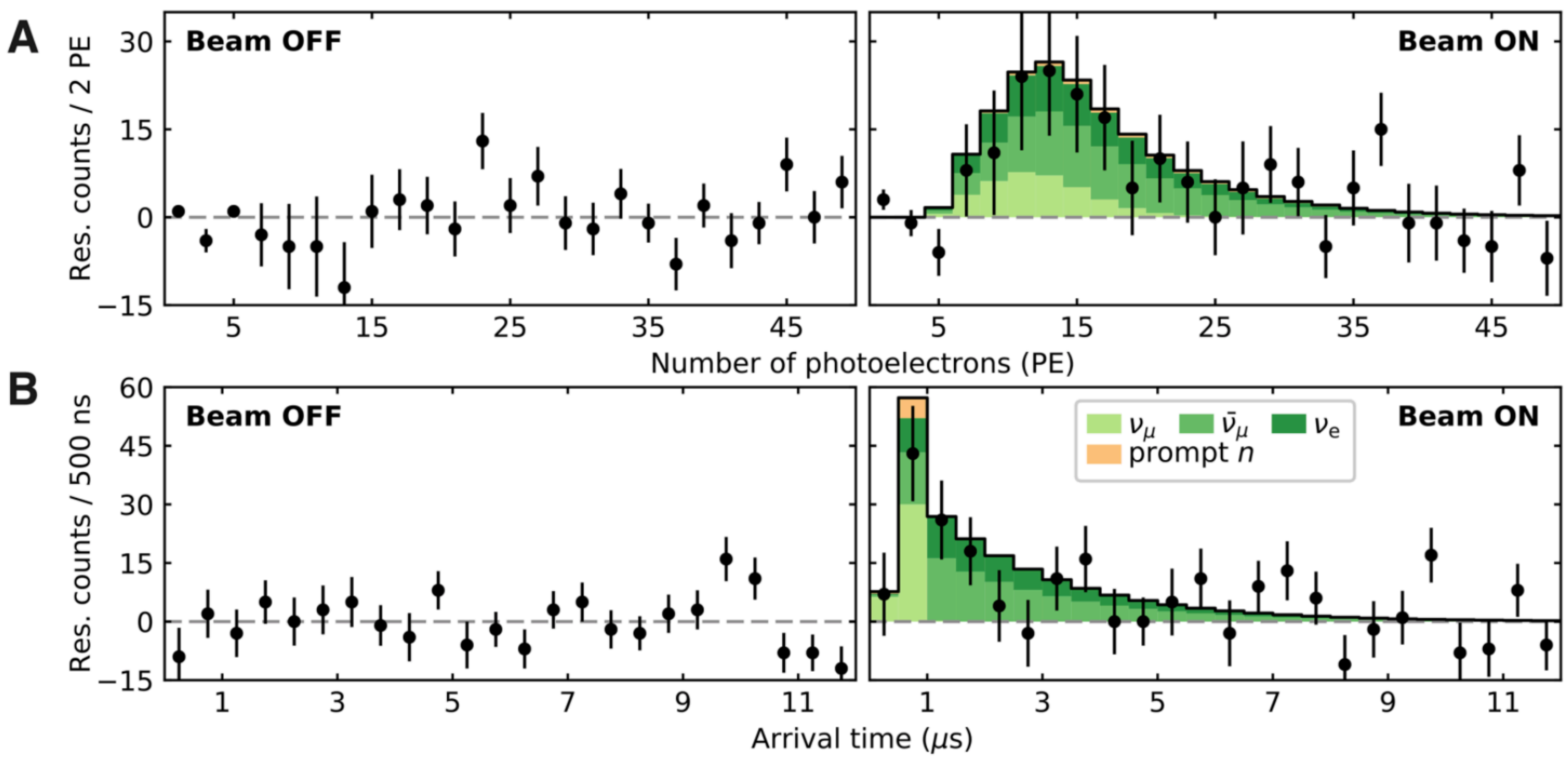
If you measure it you can probe BSM physics.

COHERENT@SNS-ORNL

Science REPORTS

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

Observation of coherent elastic neutrino-nucleus scattering

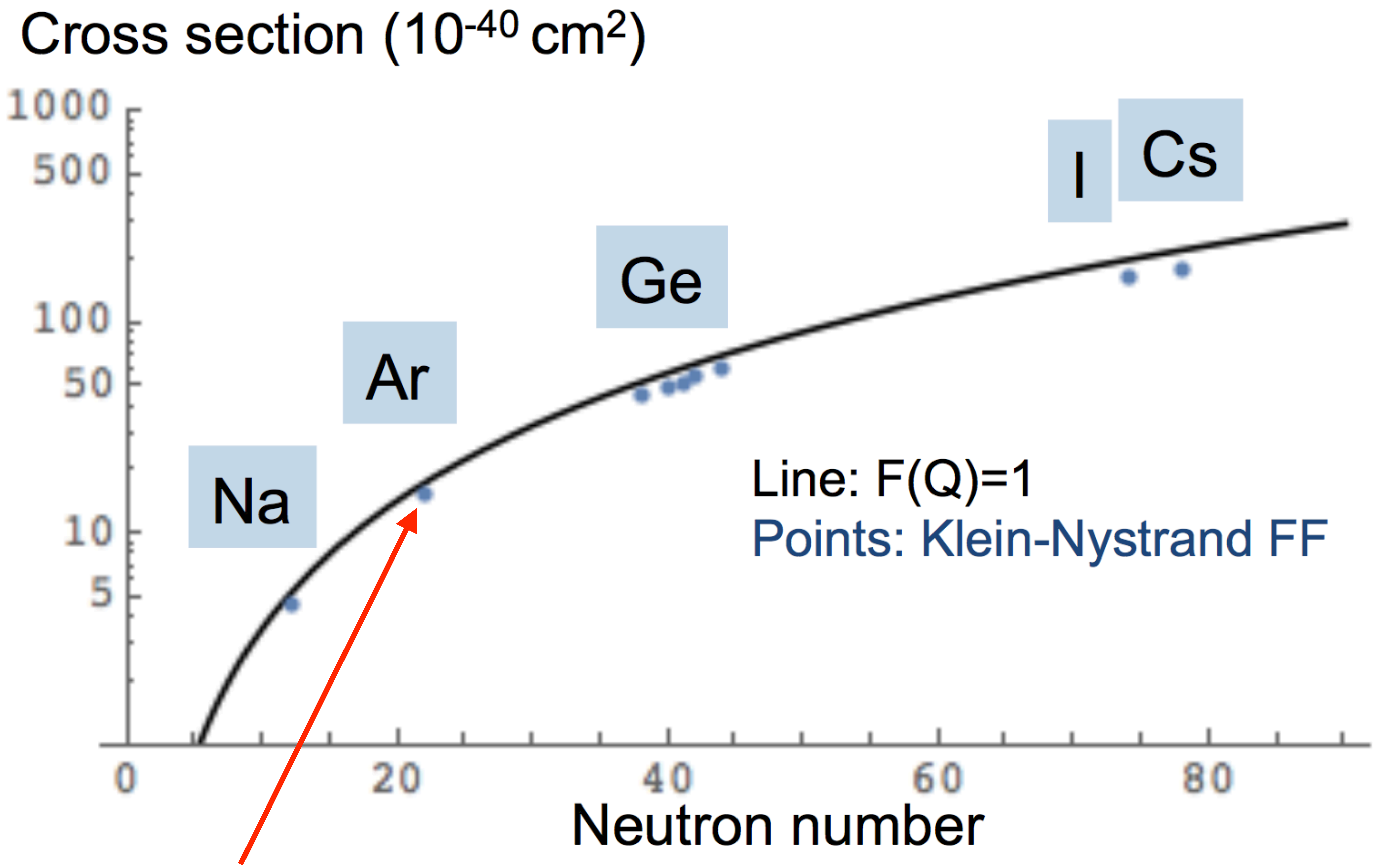


$$\frac{d\sigma}{dT}(E_\nu, T) \simeq \frac{G_F^2}{4\pi} M \left[1 - \frac{MT}{2E_\nu^2}\right] Q_W^2 F_W^2(q^2) \propto N^2 \qquad Q_W = N - (1 - 4\sin^2\theta_W)Z$$

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

Nuclear structure information needed: elastic weak form factor

CEvNS cross section



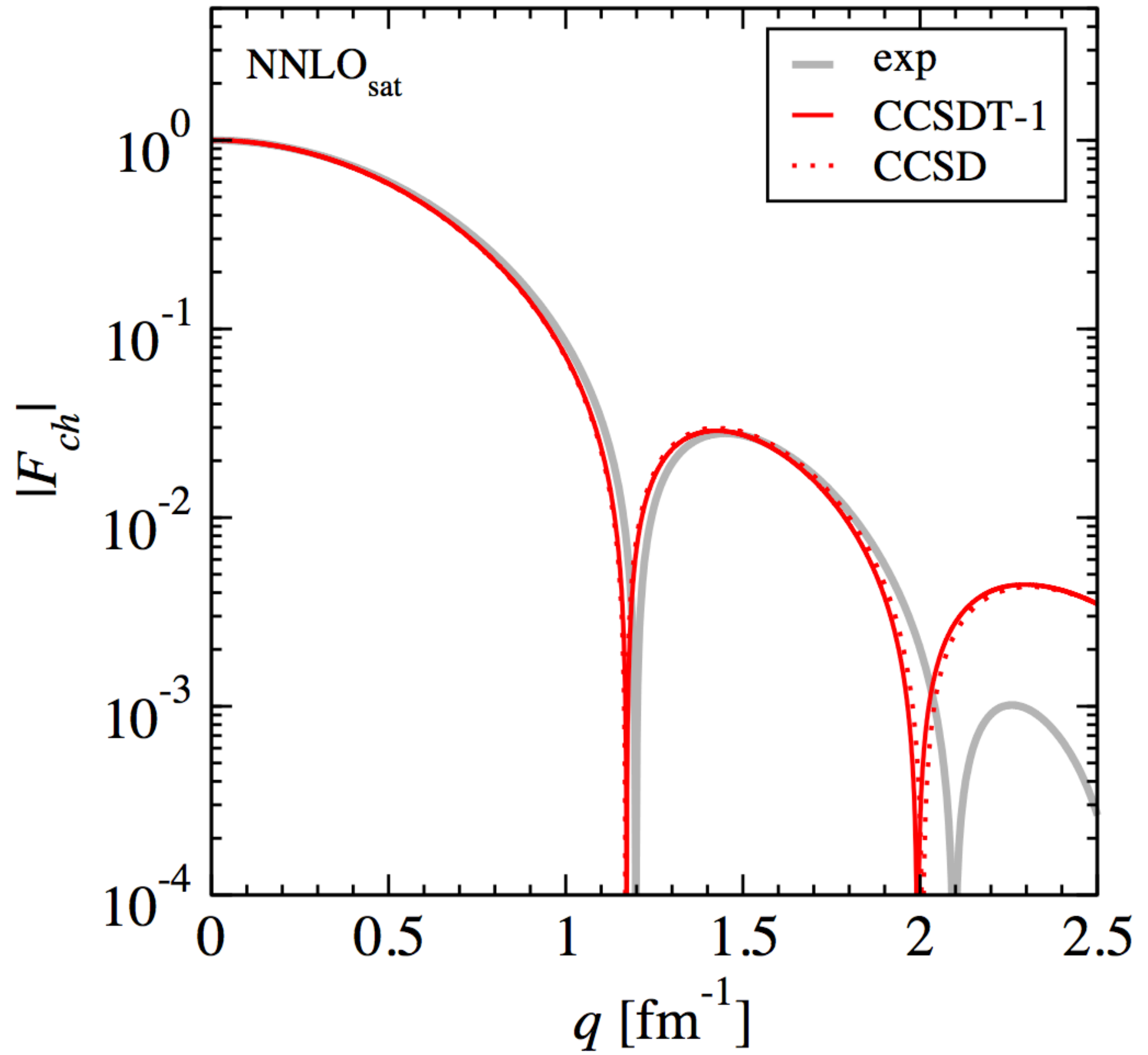
arXiv:2003.10630

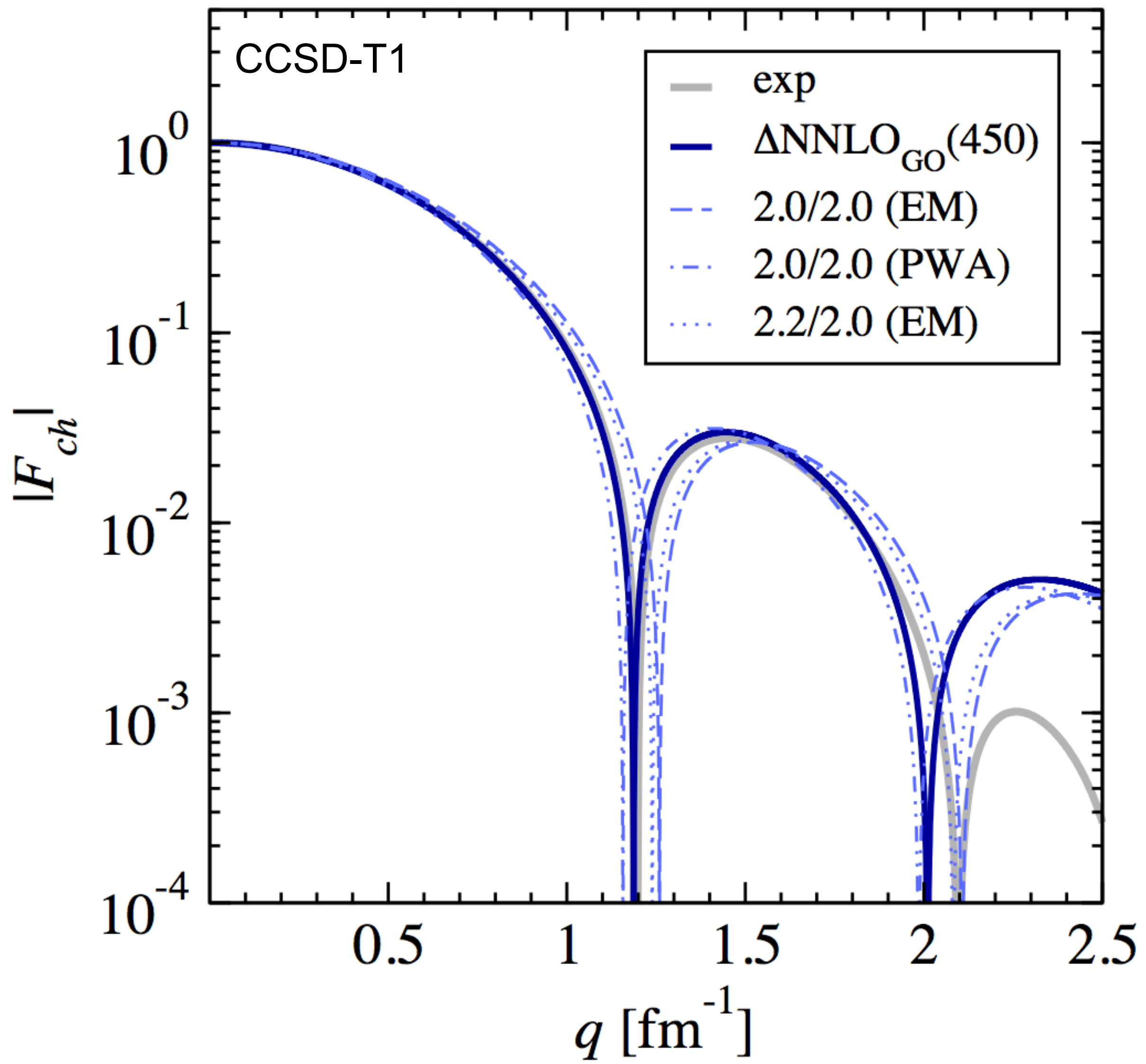
From K. Scholberg

^{40}Ar Charge Form Factor

C. Payne

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



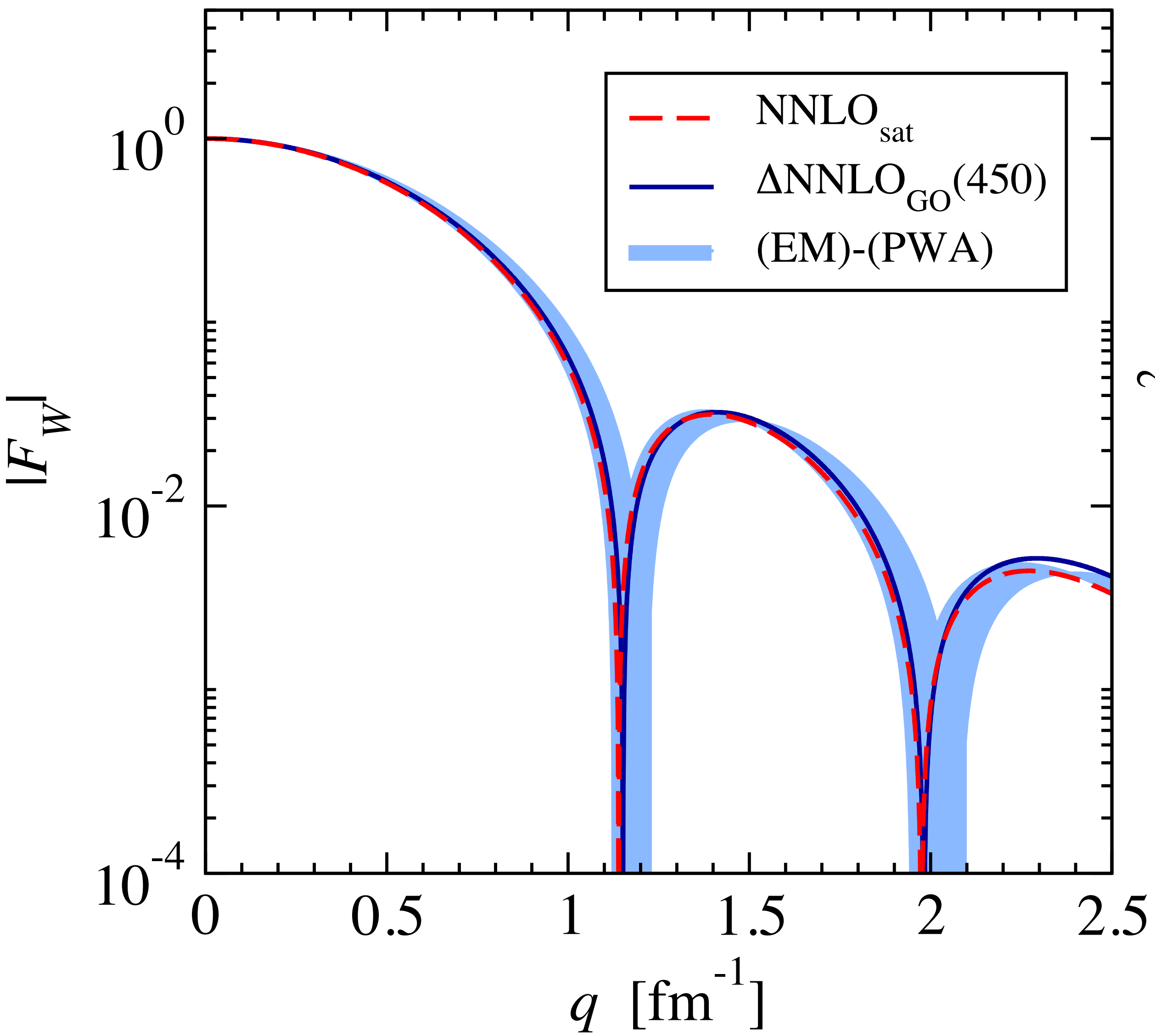


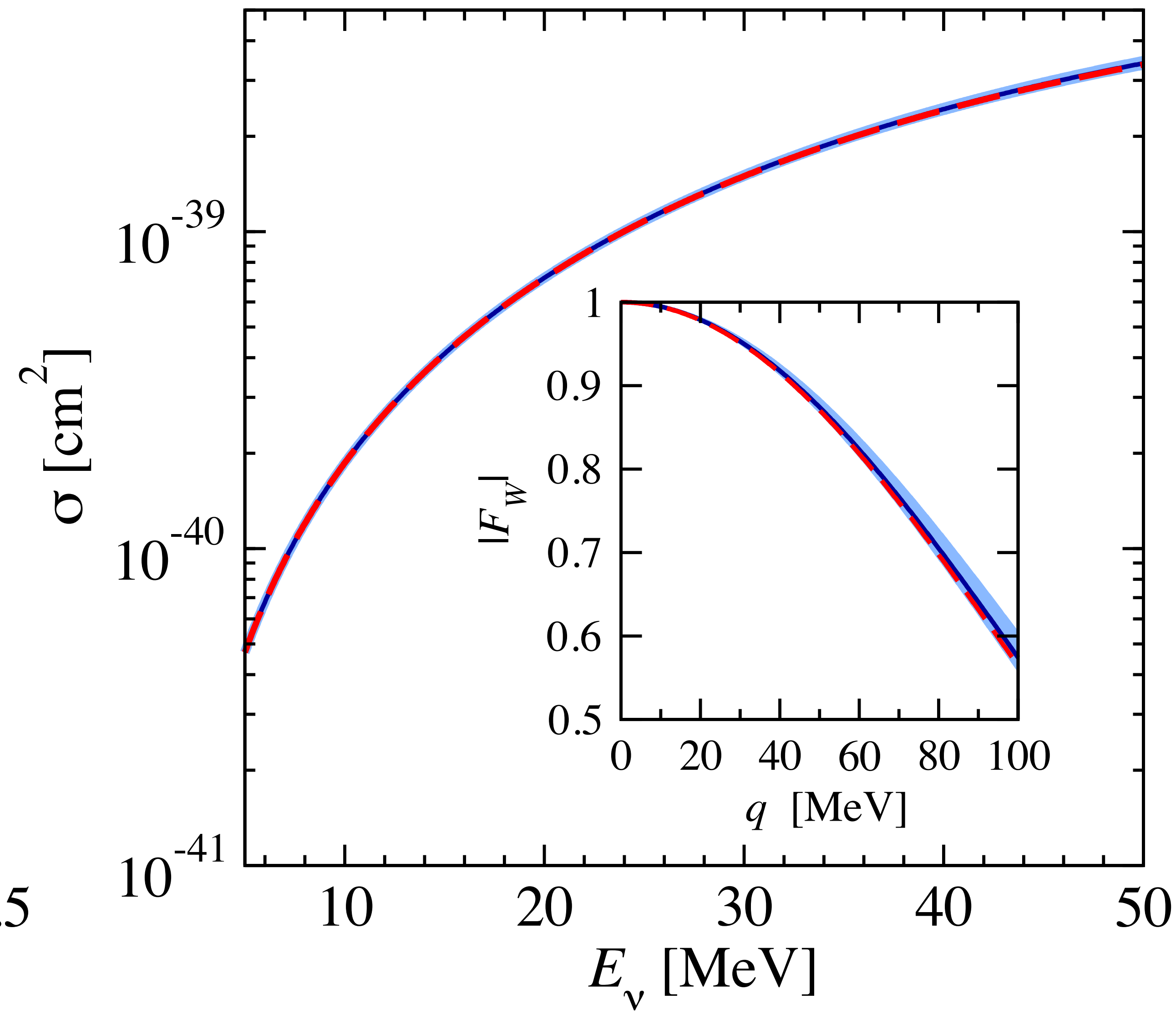
exp: in Mainz, Ottermann et. al., Nucl. Phys. A **379**, 396 (1982)

^{40}Ar Weak Form Factor

C. Payne

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

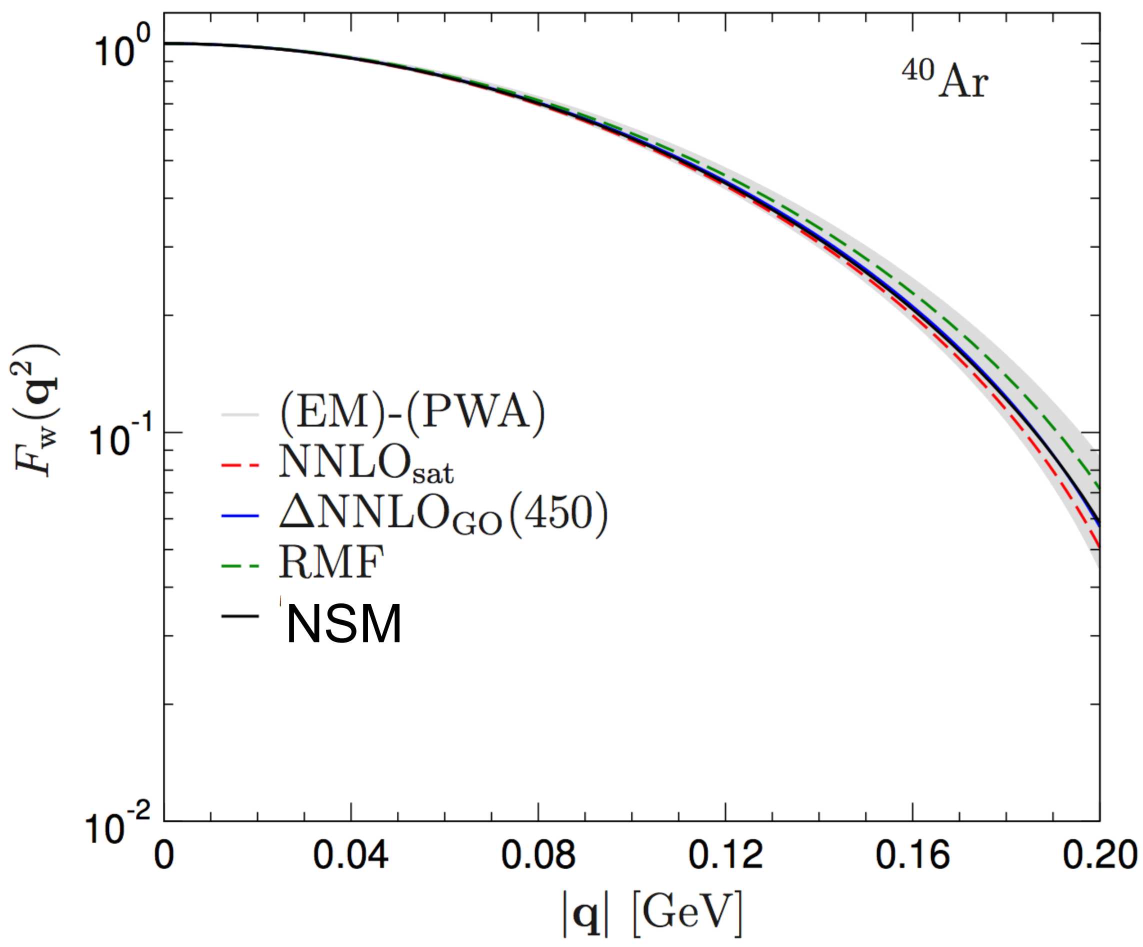




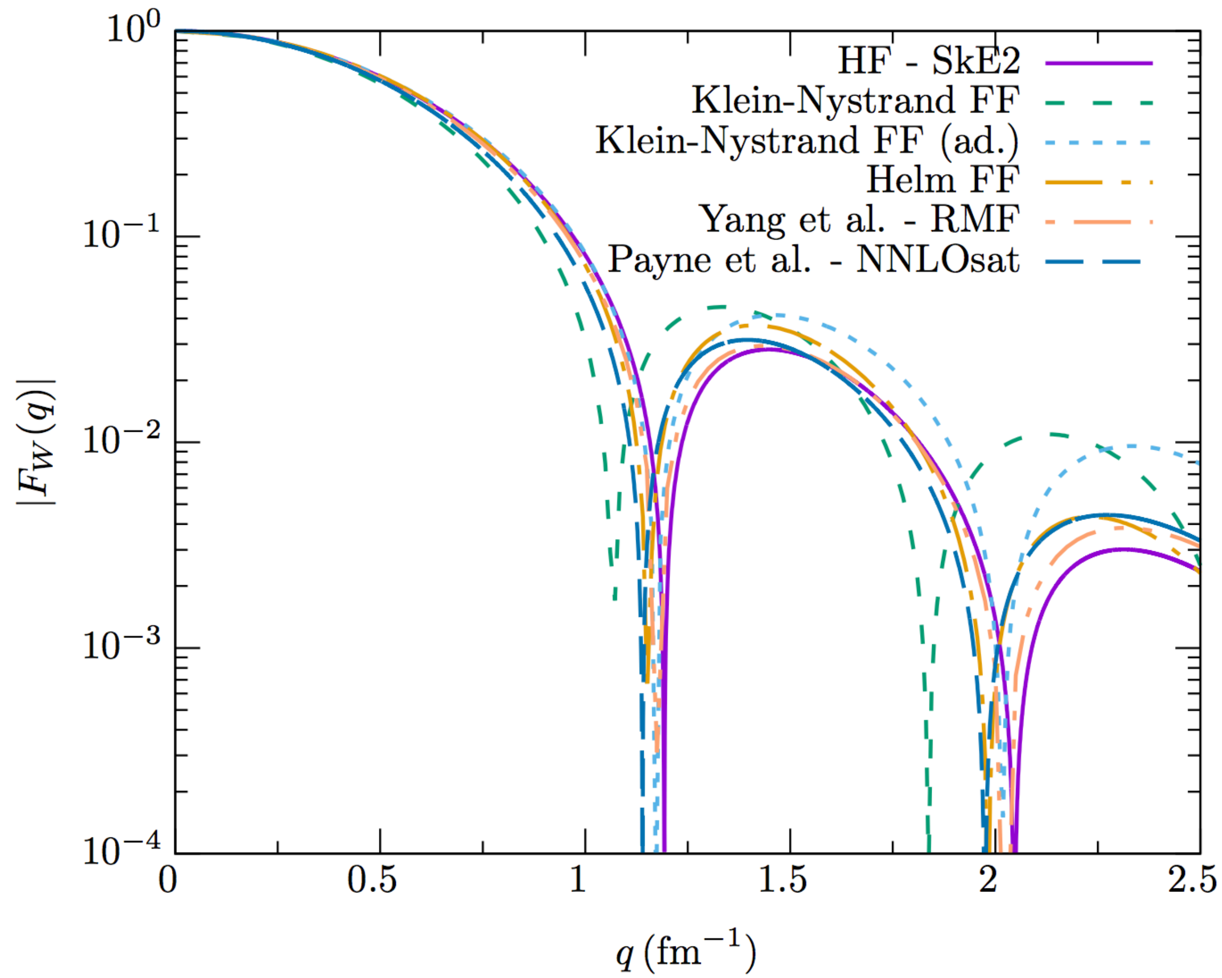
Small nuclear structure uncertainties in the cross section, in contrast to what originally estimated in Sierra, Liao, Malfatia, JHEP 1906:141 (2019)

Comparison to other calculations

Hoferichter et al., **arXiv:2007.08529**



Van Dessel et al., **arXiv:2007.03658**



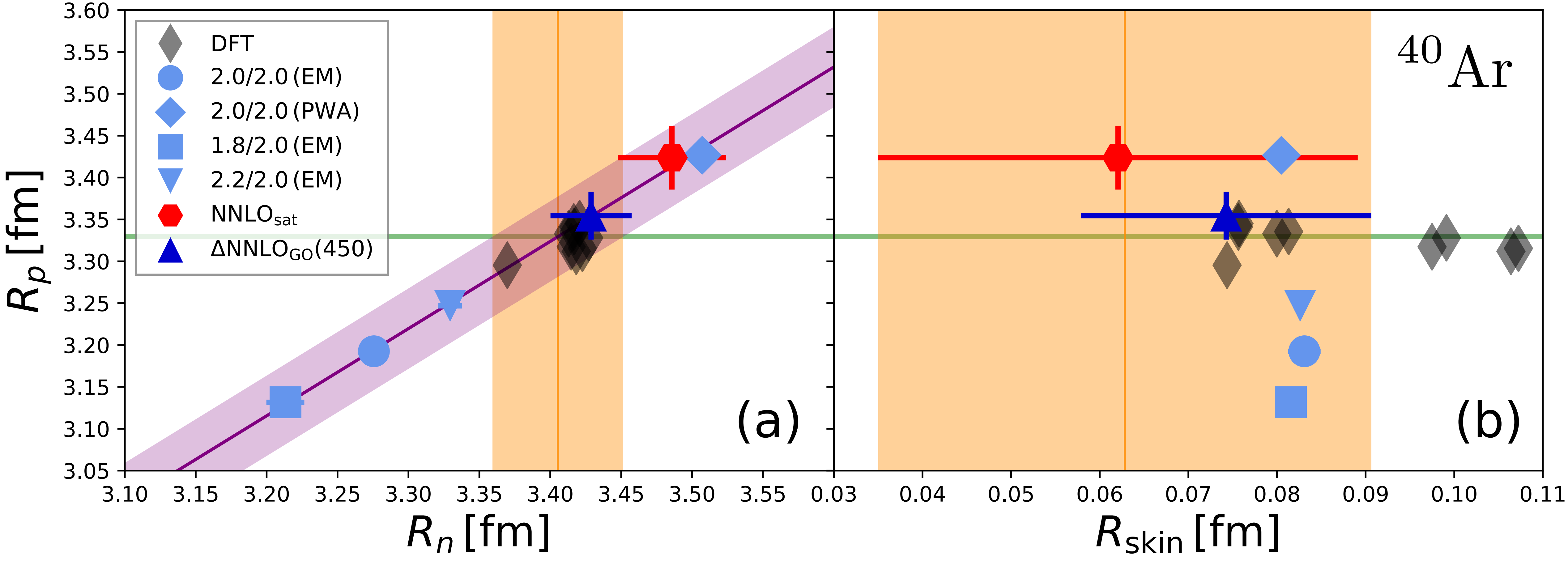
See also RMF Yang et al., Phys. Rev. C 100, 054301 (2019)
and RPA calculations in Co' et al., arXiv:2001.04684.

Confirm small nuclear structure uncertainties in the cross section.

Neutron radius and skin thickness

Perhaps R_n and R_{skin} can be extracted from coherent elastic neutrino scattering

Amanik and McLaughlin, J. Phys. G: Nucl. Part. Phys. **36** 015105 (2009)
Cadeddu et al., Phys. Rev. Lett. **120**, 072501 (2018)



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

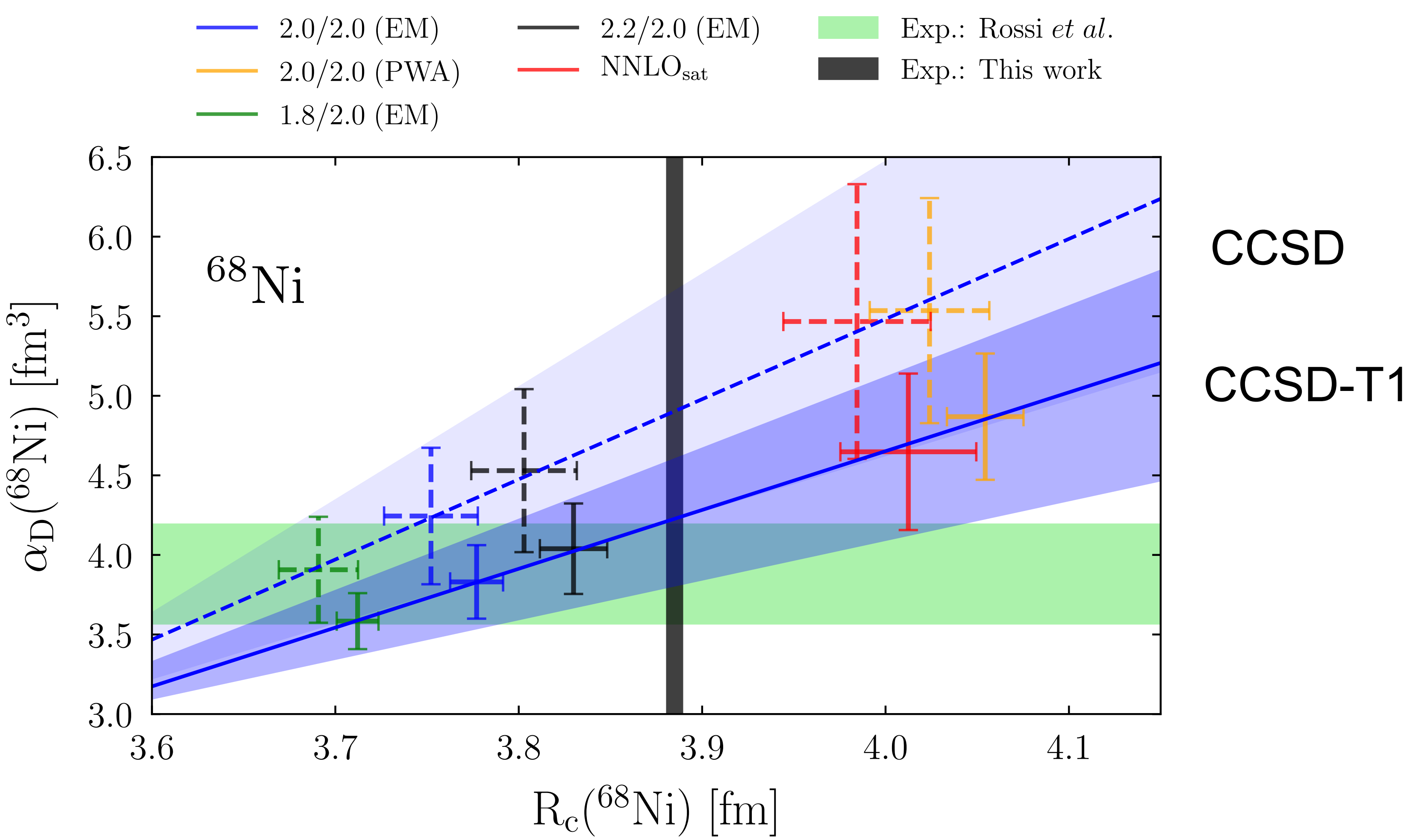
^{68}Ni neutron skin thickness

Neutron rich nucleus: ^{68}Ni, unstable (Z=28 and N=40)

J. Simonis

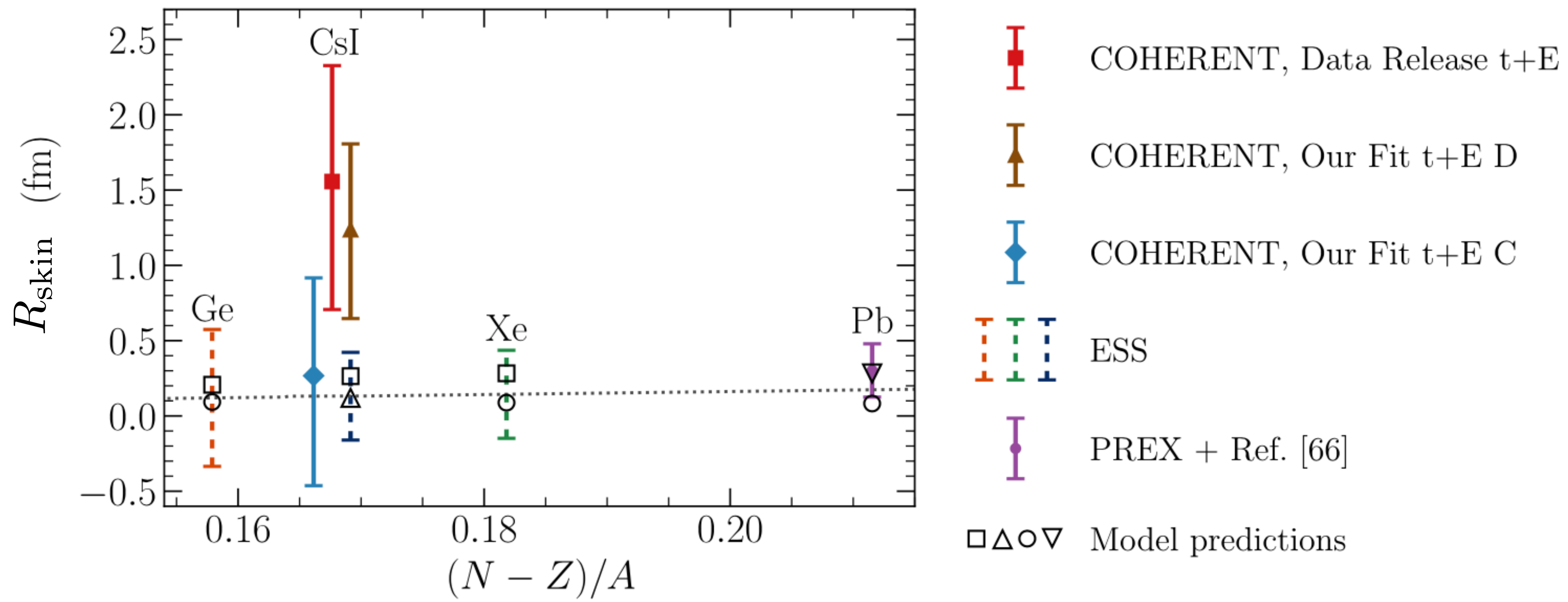
S. Kaufmann, J. Simonis, S.B. et al., PRL **124** 132502 (2020)

Hamiltonian	α_D	R_p	R_n	R_{skin}	R_c
1.8/2.0 (EM)	3.58(18)	3.62(1)	3.82(1)	0.201(1)	3.70(1)
2.0/2.0 (EM)	3.83(23)	3.69(2)	3.89(2)	0.202(3)	3.77(1)
2.2/2.0 (EM)	4.04(28)	3.74(2)	3.94(2)	0.203(4)	3.82(2)
2.0/2.0 (PWA)	4.87(40)	3.97(2)	4.17(3)	0.204(8)	4.05(2)
$NNLO_{sat}$	4.65(49)	3.93(4)	4.11(5)	0.183(8)	4.00(4)



Neutron radius and skin thickness

Coloma, Esteban, Gonzalez-Garcia, Menendez, 2006.08624



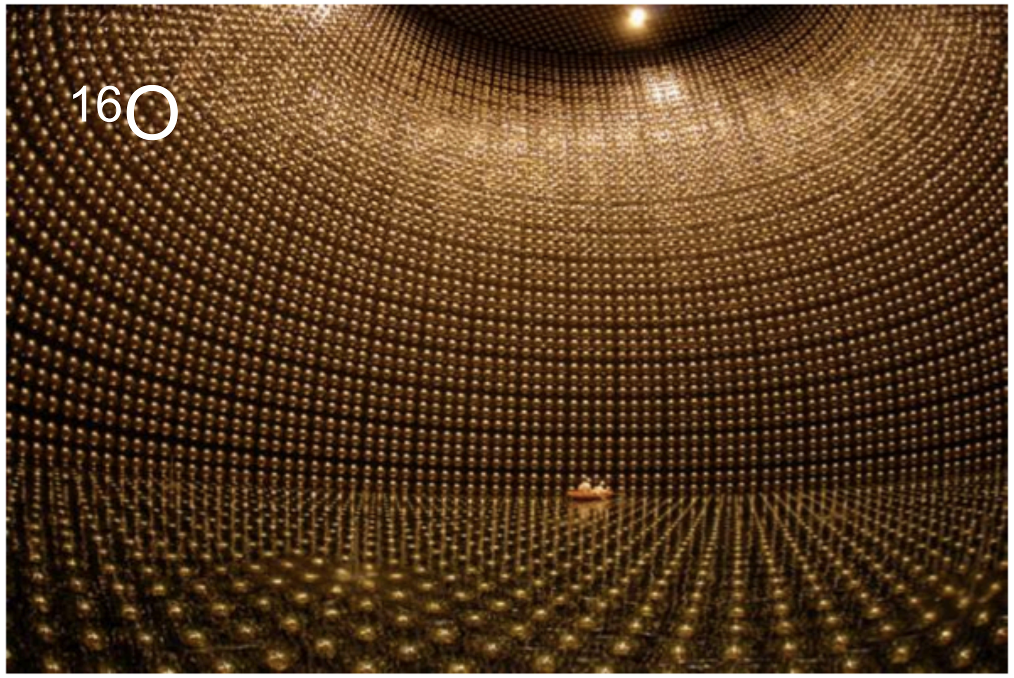
Cadeddu et al., Phys. Rev. Lett. **120**, 072501 (2018)

CsI $R_n = 5.5^{+0.9}_{-1.1}$ fm $\quad R_{\rm skin} = 0.7^{+0.9}_{-1.1}$ fm

For discussion: what are the prospects to extract $R_{\rm skin}$ for ^{40}Ar from COHERENT?

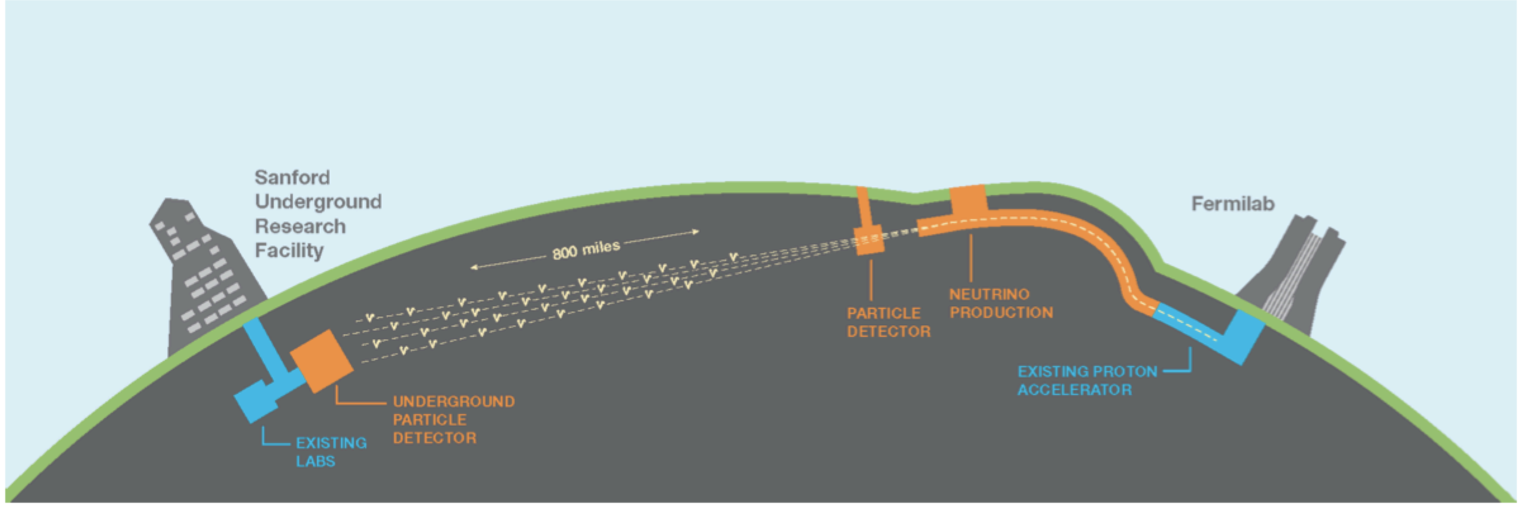
Inelastic neutrino scattering

Long baseline neutrino experiments aim at measuring fundamental neutrino properties.
Detectors are made by complex nuclei (^{12}C, ^{16}O, ^{40}Ar, ...)



T2K /T2HK

MiniBooNE, Minerva, ...



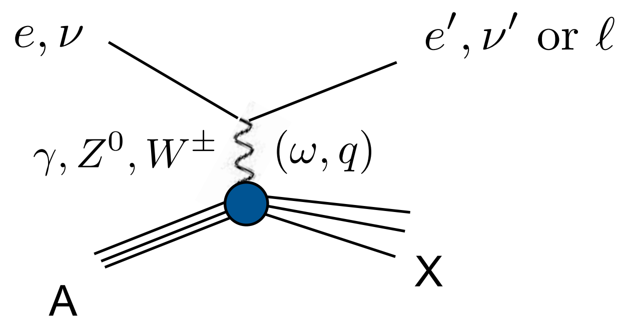
DUNE

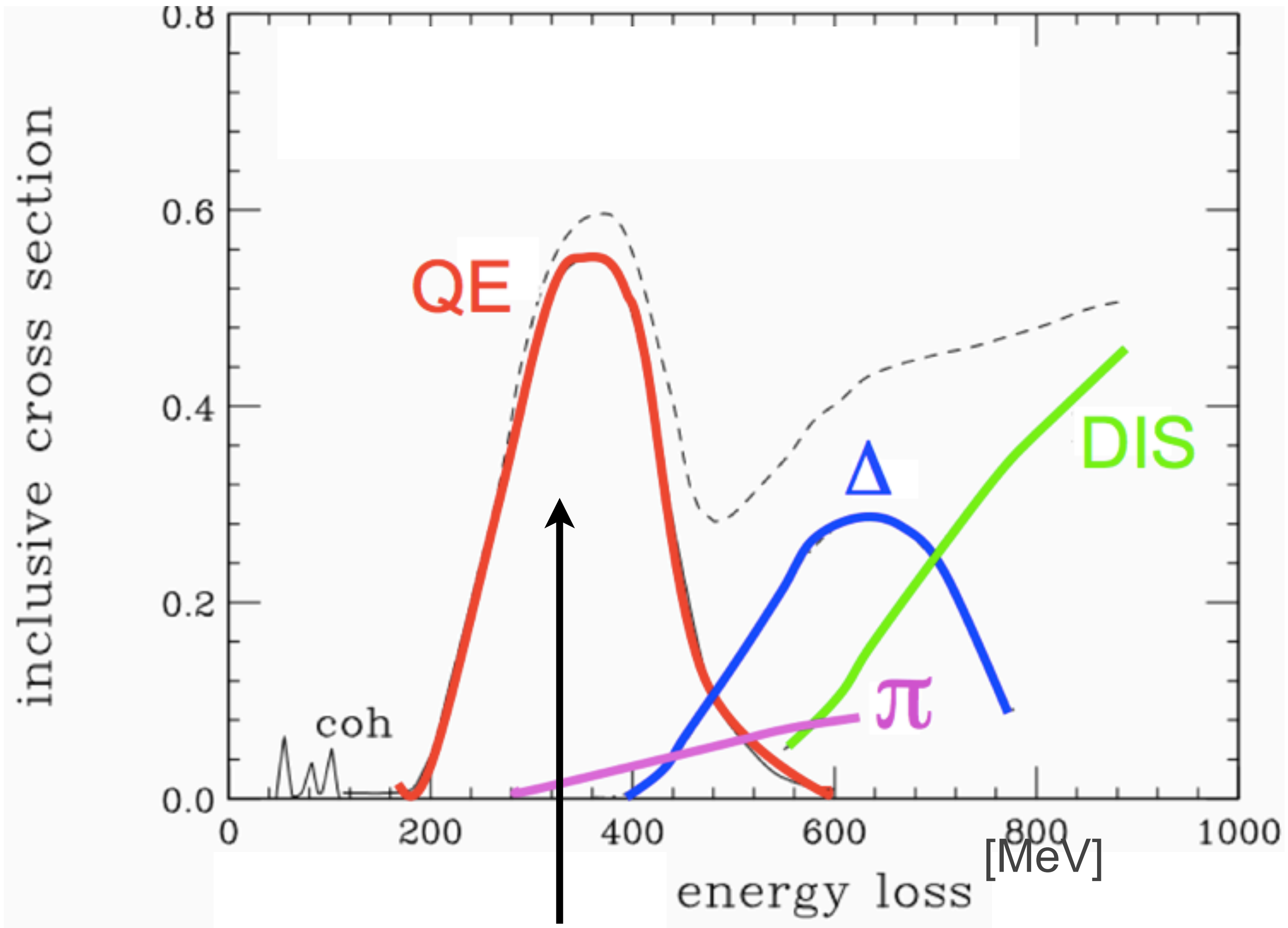
Can we perform ab initio calculations of neutrino nucleus cross sections?

$R(\omega, q) \rightarrow$ See work by Lovato et al.

Lepton-nucleus scattering

Neutrino scattering ⇔ electron scattering





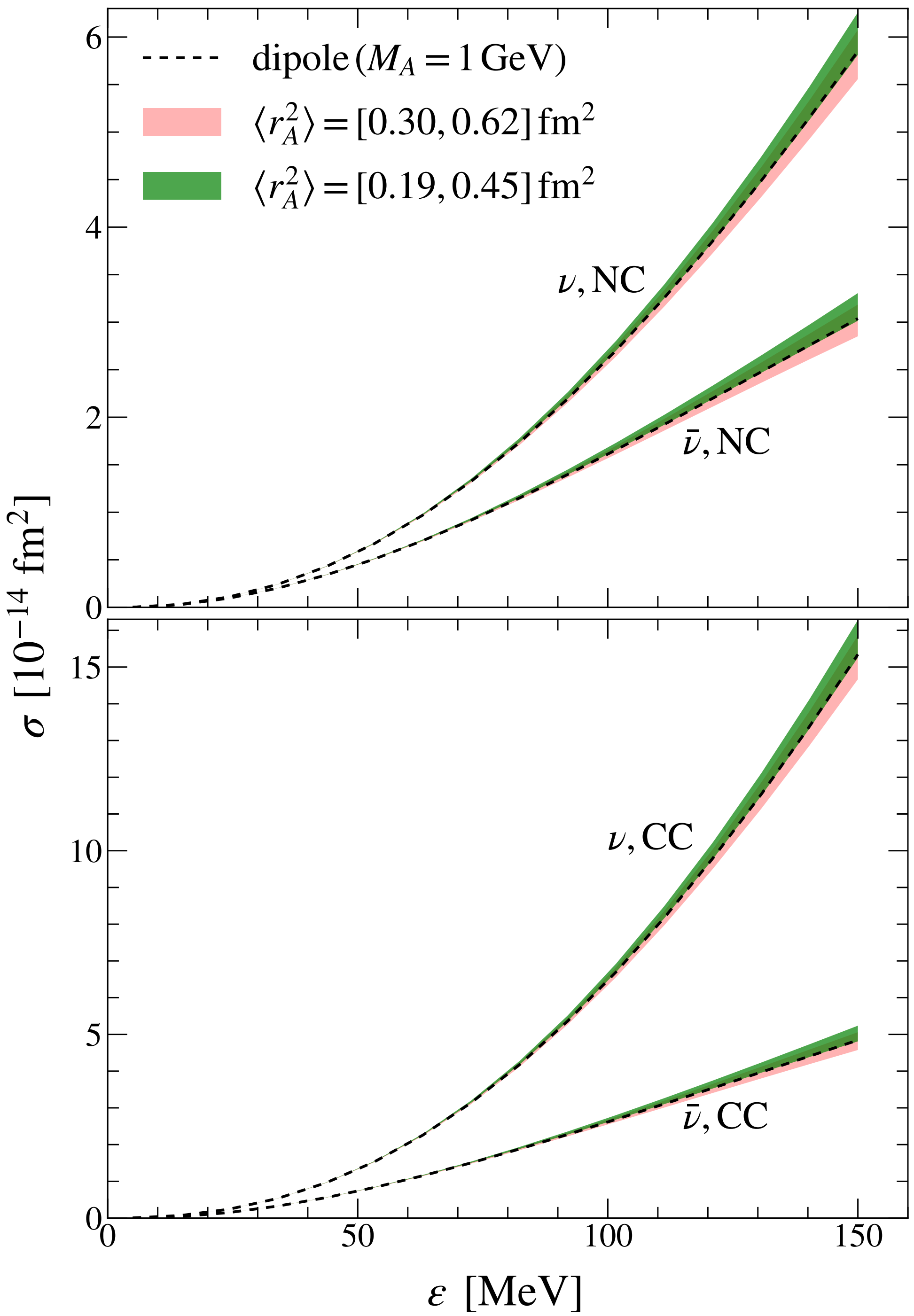
Window of opportunity for our ab initio nuclear theory

Neutrino Deuteron scattering

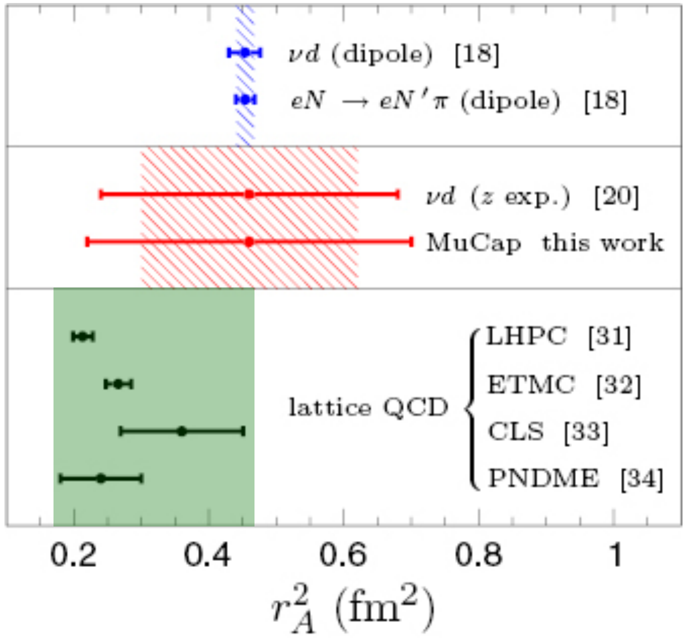
B. Acharya and S.B., PRC **101**, 015505 (2019)

B. Acharya

- Consider the simplest nucleus to simplify structure part and focus on the multipole expansion of the electroweak operators
- Benchmark previous results with one- and two-body currents (up to N2LO)
- For the deuteron we find that the largest source of uncertainty at low energy is coming from “single nucleon physics”



$$G_A(Q^2) = g_A[1 - \langle r_A^2 \rangle Q^2/6]$$

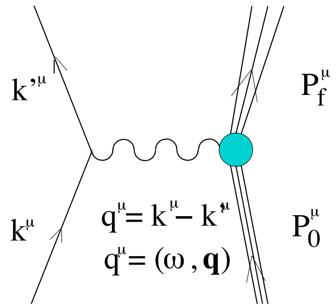


Hill et al,

Prog.Rep (2018)

Coulomb sum rule

Total strength of inelastic longitudinal response function



$$\mathrm{CSR}(q) = \int d\omega \; R_L^{in}(\omega, \mathbf{q})$$

$$R_L^{in}(\omega, \mathbf{q}) = \sum_f |\langle f|\rho(\mathbf{q})|\mathbf{0}\rangle|^{\mathbf{2}} \delta(\omega - \mathbf{E_f} + \mathbf{E_0})$$

Can be measured from electron scattering

Theory methods:

1) Expand charge operator in multipoles and compute CSR $\rho(\mathbf{q}) = \sum_i^A e^{i\mathbf{q}\mathbf{r}_i} = \sum_{\mathcal{J}} C^{\mathcal{J}}(\mathbf{q})$

2) Calculate CSR as expectation value

$$\mathrm{CSR}(q) = Z + \langle 0| \sum_{i \neq j} e^{i\mathbf{q}\cdot(\mathbf{r}_i - \mathbf{r}_j)} |0\rangle - |F_{el}(\mathbf{q})|^2 Z^2$$

$$\langle 0| \sum_{i \neq j} e^{i\mathbf{q}\cdot(\mathbf{r}_i - \mathbf{r}_j)} |0\rangle = Z(Z-1) f_2(|\mathbf{q}|)$$

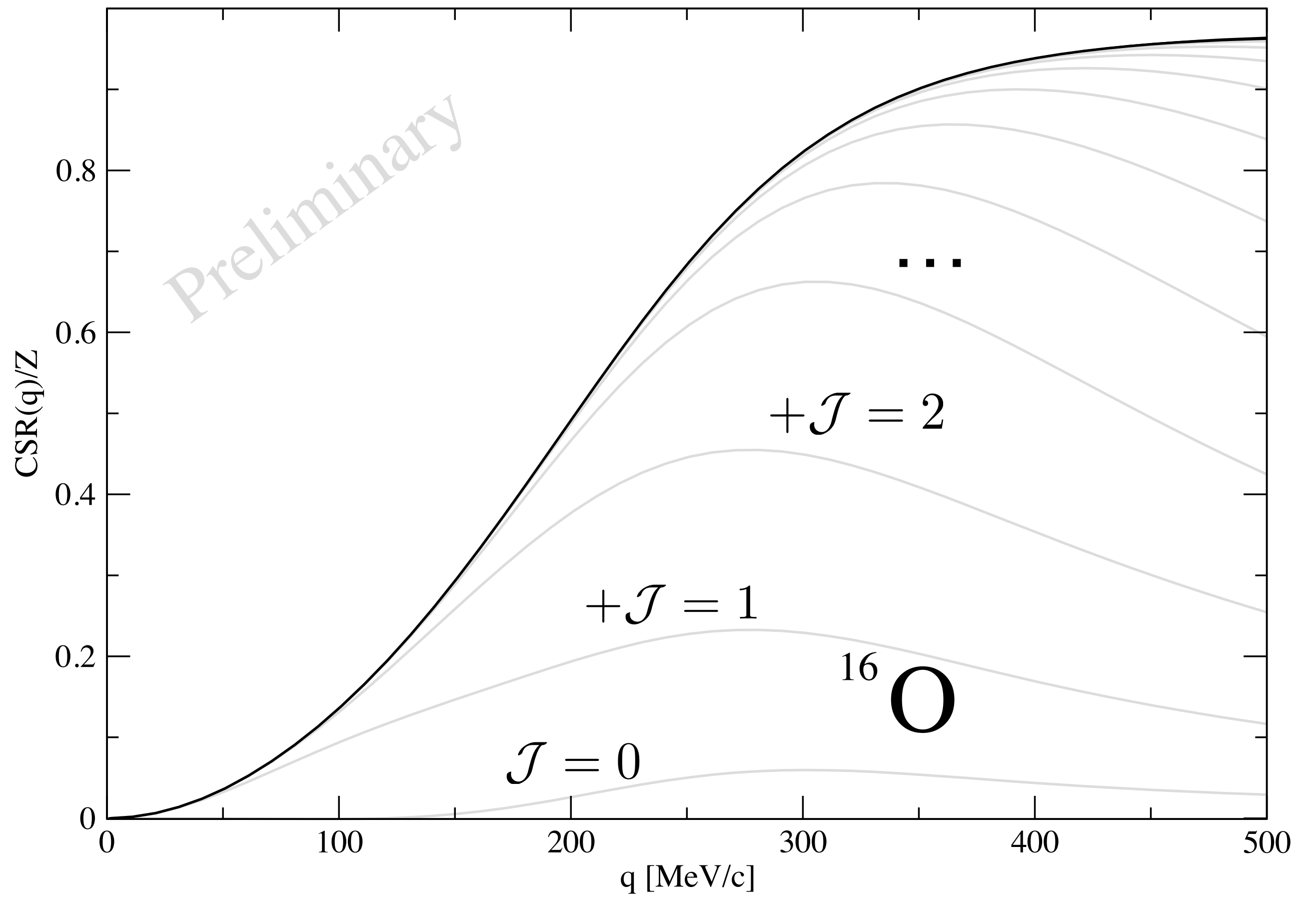
← Fourier transform of the proton-proton correlation function

Coulomb sum rule

Unpublished

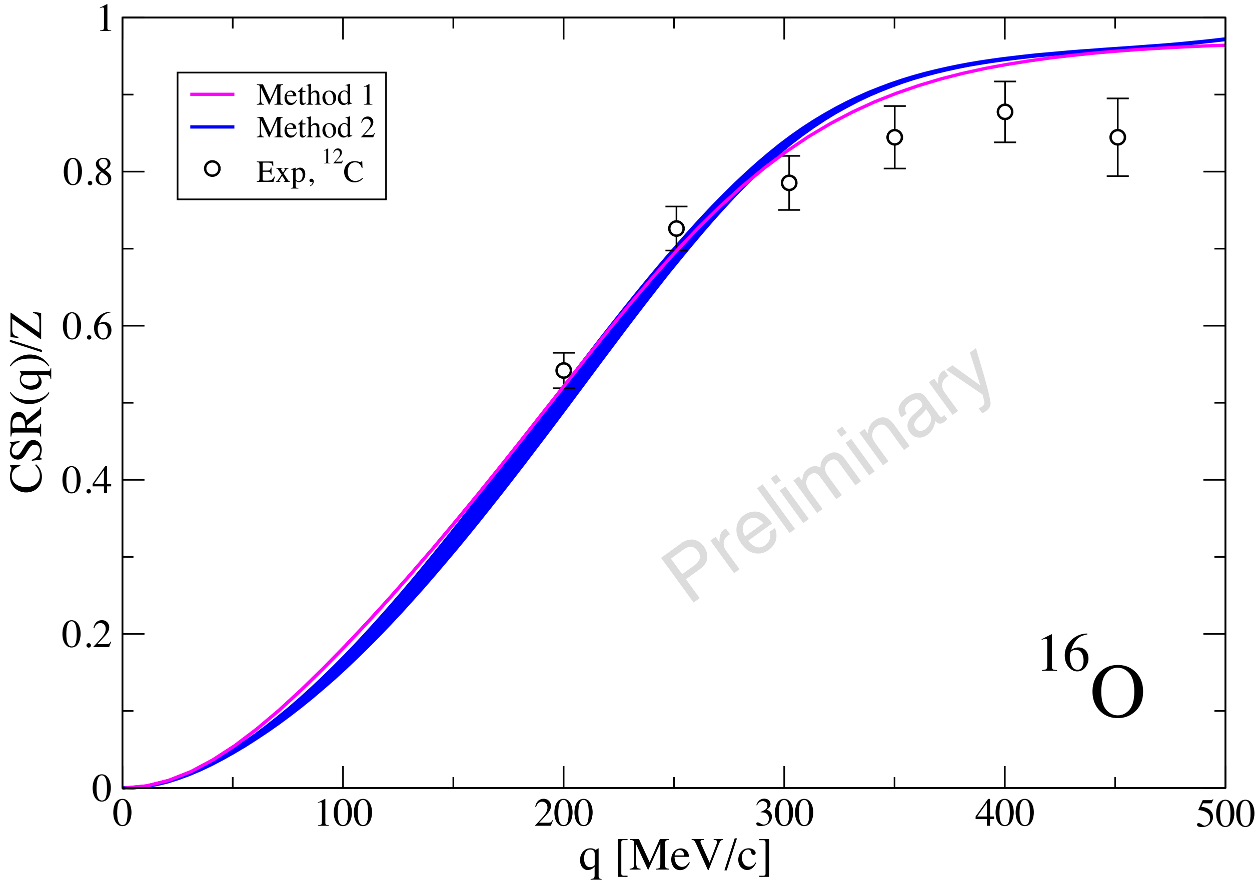
J.E. Sobczyk

Recursive sum in method 1



With chiral NN interactions at N^3LO

Comparison of methods



Outlook

- **Ab initio nuclear theory is has done enormous progress in the last decade.**
- **This theory has been validated against electromagnetic and weak data.**
- **Ab initio theory can now contribute to searches for BSM physics and can calculate the neutron skin thickness, at least in selected nuclei.**

We could look at ^{23}Na, using deformed CC, see S. Novario et al., arXiv:2007.06684

Thanks to all my collaborators

B. Acharya, N. Barnea, G. Hagen, **W. Jiang**, **M. Miorelli**, G. Orlandini, T. Papenbrock, **C. Payne**, **J. Simonis**, A. Schwenk, **J.E. Sobcyk** and many more

Thanks for your attention!