Coupled cluster calculations for ν scattering on medium-mass nuclei

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In collaboration with
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Improving the Art of Neutrino-Nuclei Modelling with Charged Lepton Scattering Data
29/03/2022

Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
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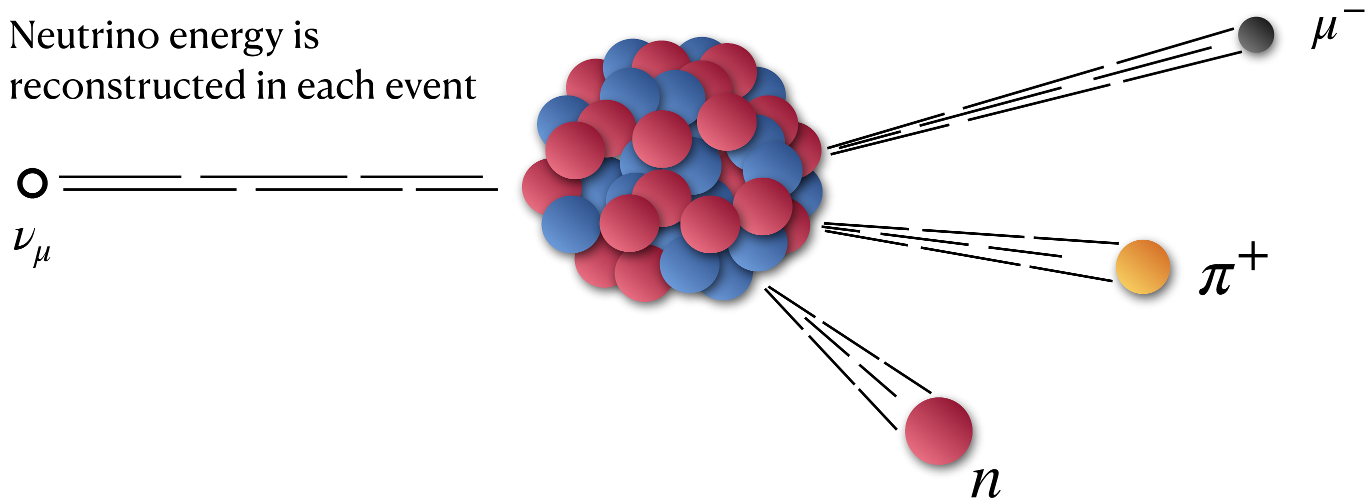
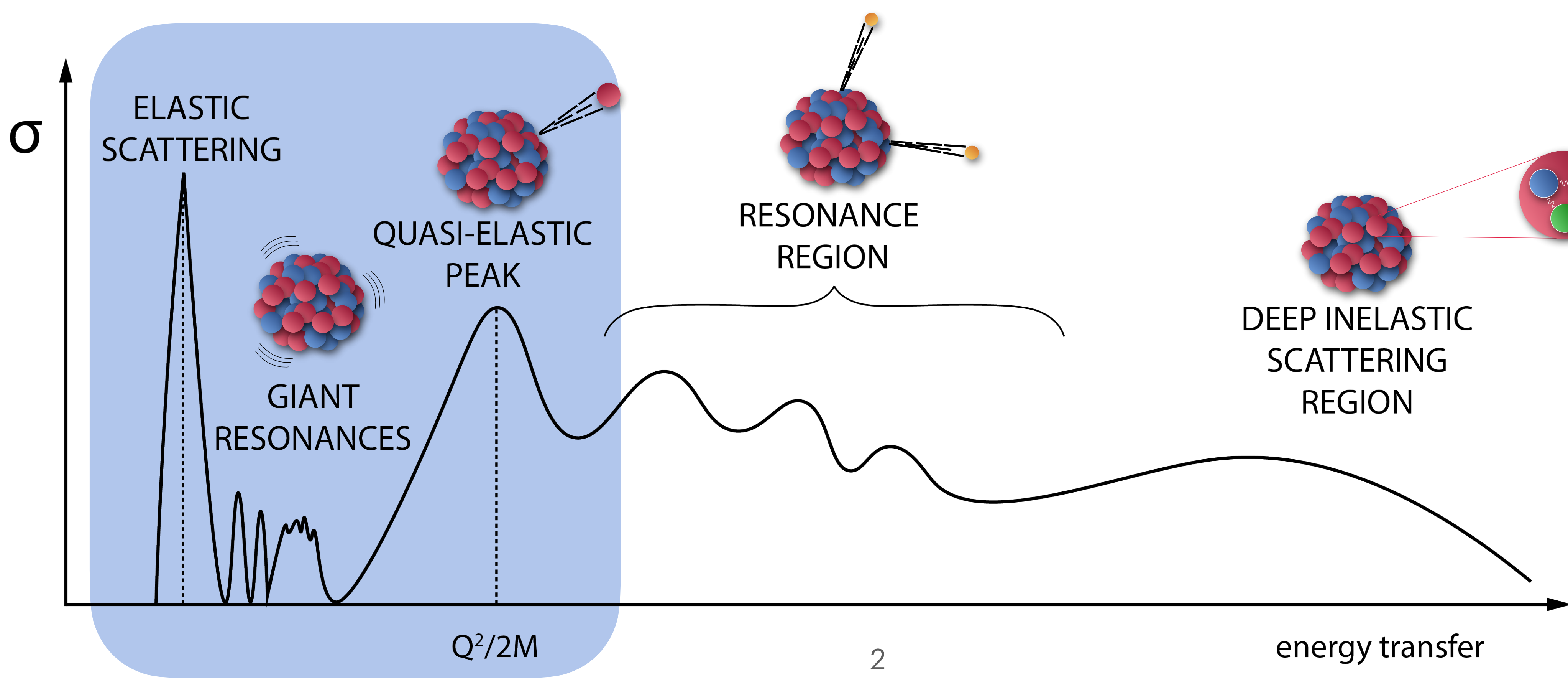
Alexander von Humboldt Stiftung / Foundation

Motivation

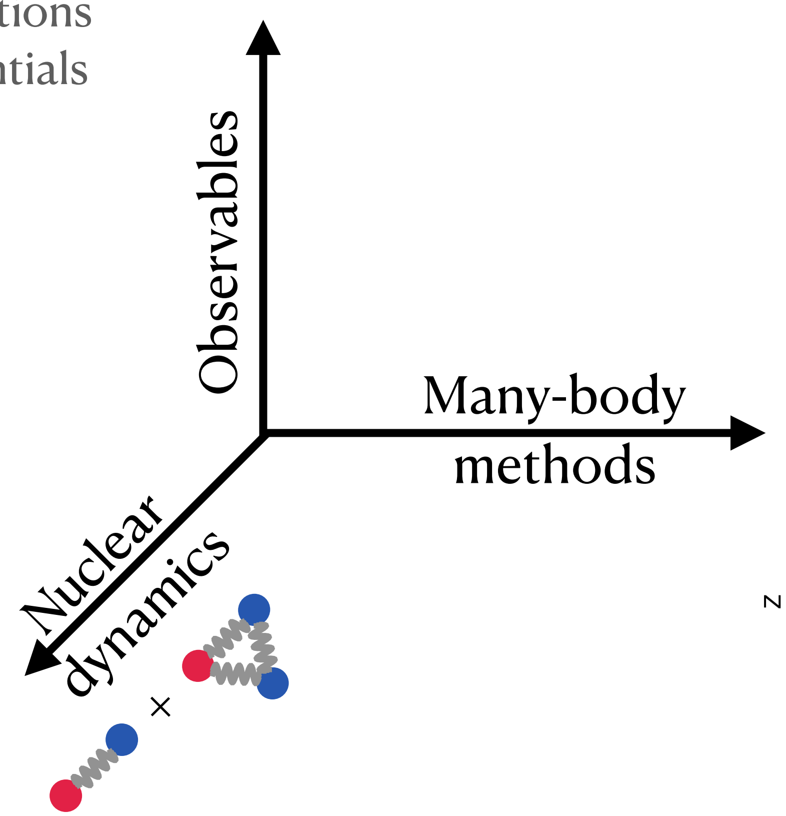

Neutrino energy is
reconstructed in each event
ν_μ
μ^-
π^+
n

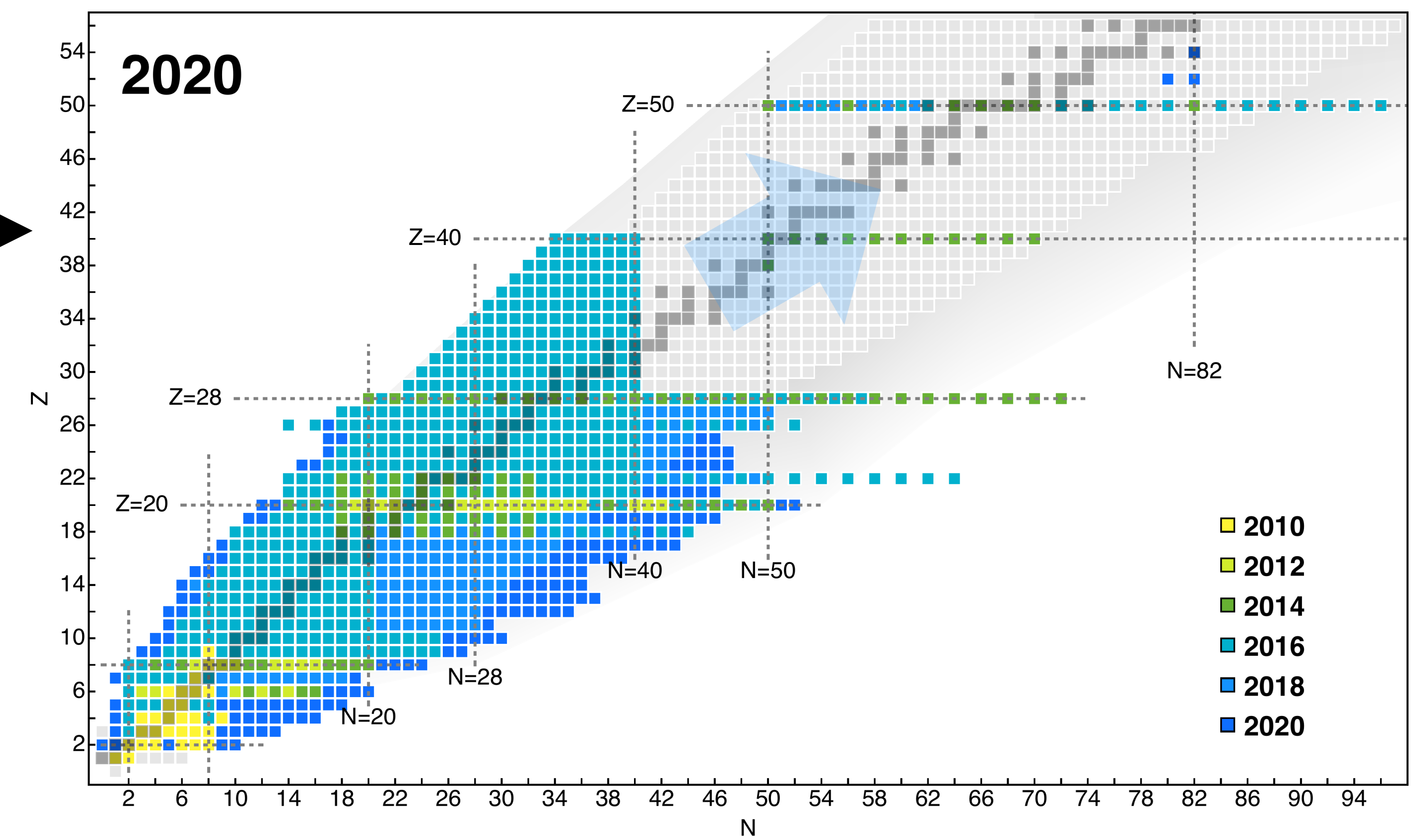

σ
ELASTIC
SCATTERING
GIANT
RESONANCES
QUASI-ELASTIC
PEAK
RESONANCE
REGION
DEEP INELASTIC
SCATTERING
REGION
Q²/2M
energy transfer

Motivation

- ➡ Nuclear responses
- ➡ Spectral functions
- ➡ Optical potentials

...

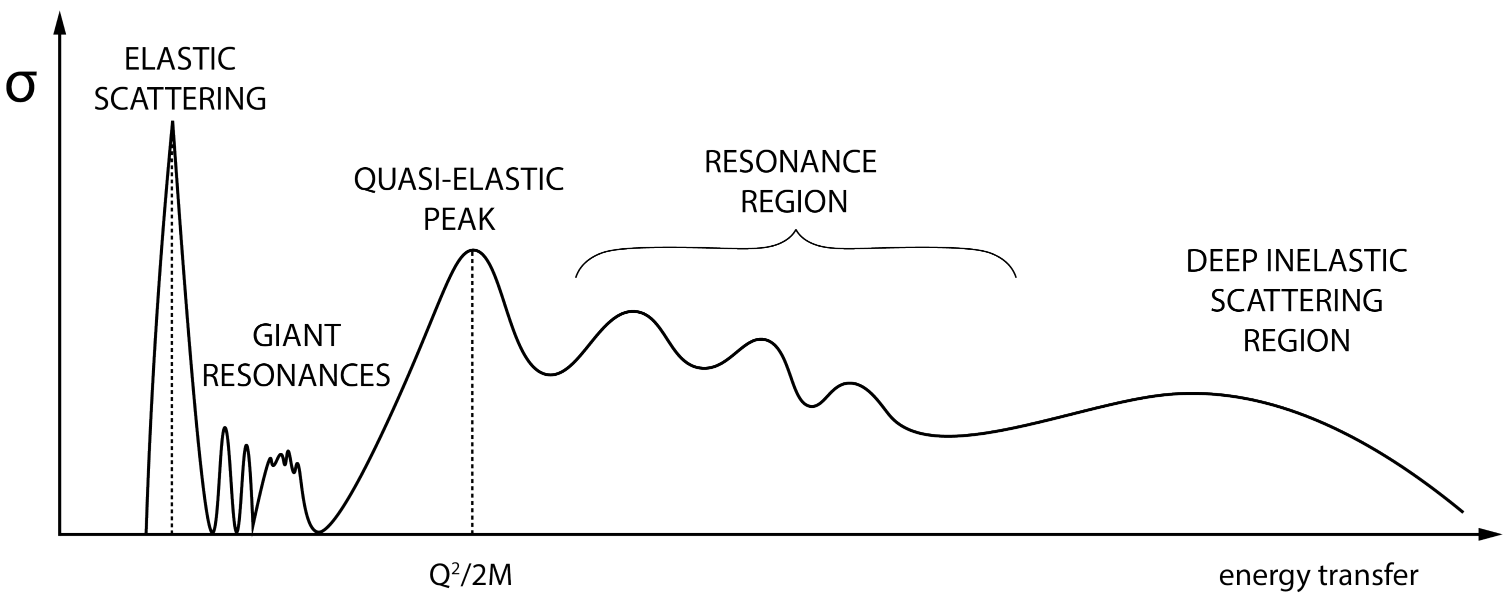




➡ **Neutrinos challenge ab initio nuclear theory**

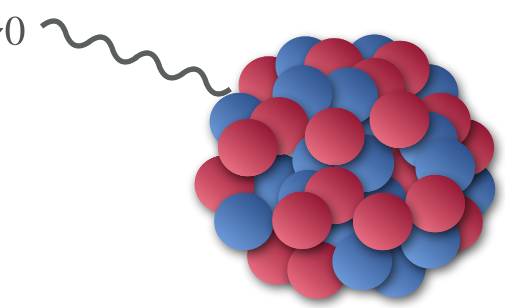
➡ **Controllable approximations within ab initial nuclear theory**

Nuclear response



$$J_\mu = (\rho, \vec{j}) \,|\, \Psi \rangle$$

$\gamma, W^\pm, Z^0$



$$\sigma \propto L^{\mu\nu} R_{\mu\nu}$$

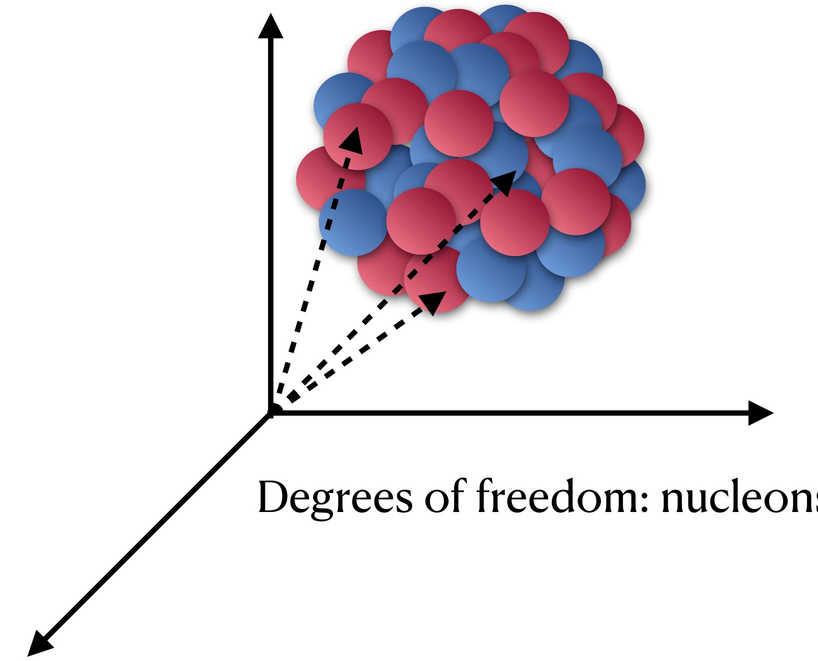
lepton tensor — nuclear responses

$$R_{\mu\nu}(\omega, q) = \sum_f \langle \Psi \,|\, J_\mu^\dagger(q) \,|\, \Psi_f \rangle \langle \Psi_f \,|\, J_\nu(q) \,|\, \Psi \rangle \delta(E_0 + \omega - E_f)$$

Ab initio nuclear theory for neutrinos

Nuclear Hamiltonian

$$\mathscr{H}\,|\,\Psi\rangle = E\,|\,\Psi\rangle$$

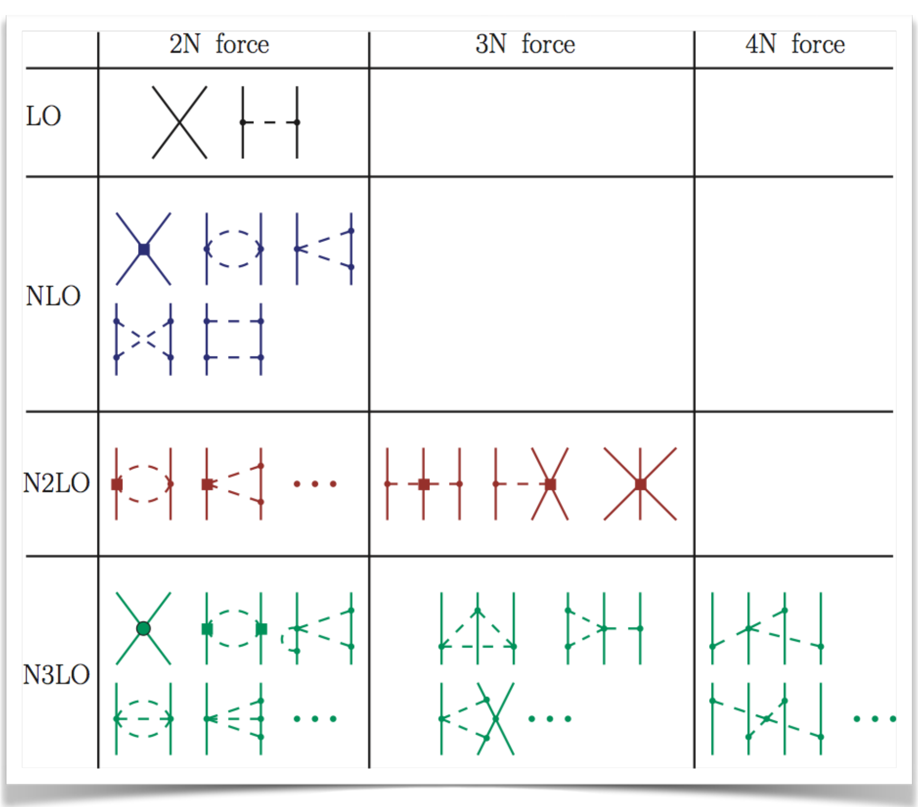


$n = 0$

$n = 2$

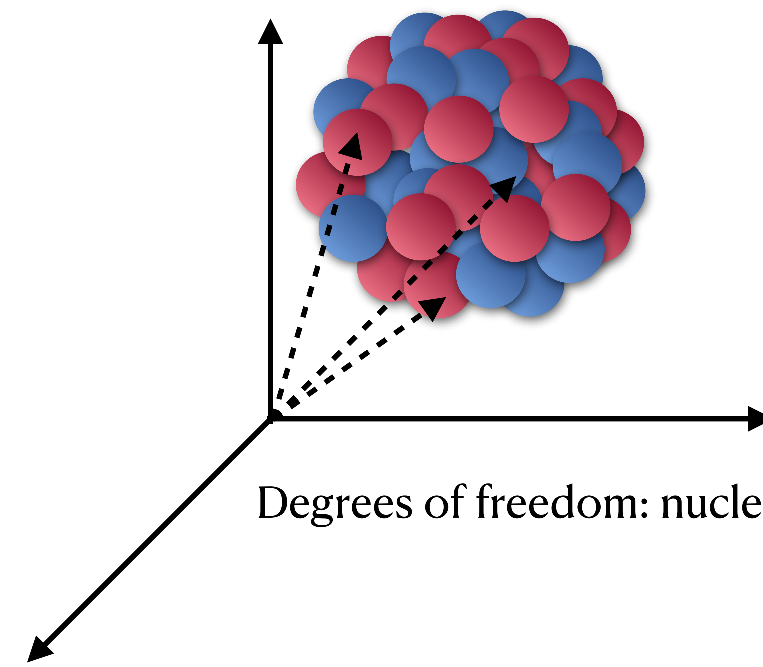
$n = 3$

$n = 4$



$$\mathscr{H} = \sum_i \frac{p_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

Ab initio nuclear theory for neutrinos



Nuclear Hamiltonian

$$\mathscr{H}\,|\Psi\rangle = E\,|\Psi\rangle$$

Electroweak currents

$$J^{\mu} = (\rho, \vec{j})$$

Many-body method

$$\mathscr{A} = \langle \Psi_m | J_\mu | \Psi_n \rangle$$

Coupled cluster method

Reference state (Hartree-Fock): $|\Psi\rangle$

Include correlations through e^T operator

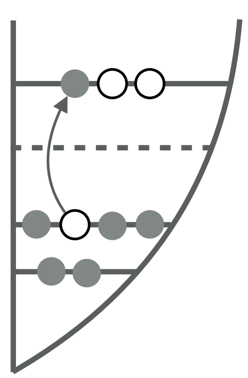
similarity transformed Hamiltonian (non-Hermitian)

$$e^{-T}\mathscr{H}e^{T}|\Psi\rangle \equiv \bar{\mathscr{H}}|\Psi\rangle = E|\Psi\rangle$$

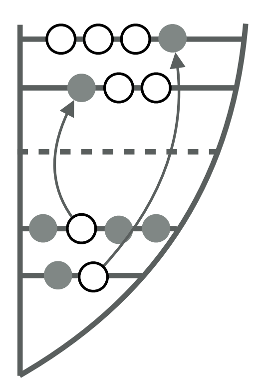
Expansion: $T = \sum t_a^i a_a^\dagger a_i + \sum t_{ab}^{ij} a_a^\dagger a_b^\dagger a_i a_j + \dots$

←coefficients obtained through coupled cluster equations

singles



doubles



Coupled cluster method

- ✓ Controlled approximation through truncation in T
- ✓ Polynomial scaling with A (predictions for ^{132}Sn and ^{208}Pb)
- ✓ Works most efficiently for doubly magic nuclei

nature physics
LETTERS
https://doi.org/10.1038/s41567-019-0450-7

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

P. Gysbers[1,2], G. Hagen[3,4*], J. D. Holt[1], G. R. Jansen[3,5], T. D. Morris[3,4,6], P. Navrátil[1], T. Papenbrock[3,4], S. Quaglioni[7], A. Schwenk[8,9,10], S. R. Stroberg[1,11,12] and K. A. Wendt[7]

***Ab initio* predictions link the neutron skin of ^{208}Pb to nuclear forces**

Baishan Hu,[1,*] Weiguang Jiang,[2,*] Takayuki Miyagi,[1,3,*] Zhonghao Sun,[4,5,*] Andreas Ekström,[2] Christian Forssén,[2,†] Gaute Hagen,[5,4,1] Jason D. Holt,[1,6] Thomas Papenbrock,[4,5] S. Ragnar Stroberg,[7,8] and Ian Vernon[9]
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Coupled-Cluster Calculations of Neutrinoless Double-β Decay in ^{48}Ca

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We use coupled-cluster theory and nuclear interactions from chiral effective field theory to compute the nuclear matrix element for the neutrinoless double-β decay of ^{48}Ca. Benchmarks with the no-core shell model in several light nuclei inform us about the accuracy of our approach. For ^{48}Ca we find a relatively small matrix element. We also compute the nuclear matrix element for the two-neutrino double-β decay of ^{48}Ca with a quenching factor deduced from two-body currents in recent *ab initio* calculation of the Ikeda sum rule in ^{48}Ca [Gysbers *et al.*, Nat. Phys. **15**, 428 (2019)].

Quasielastic response

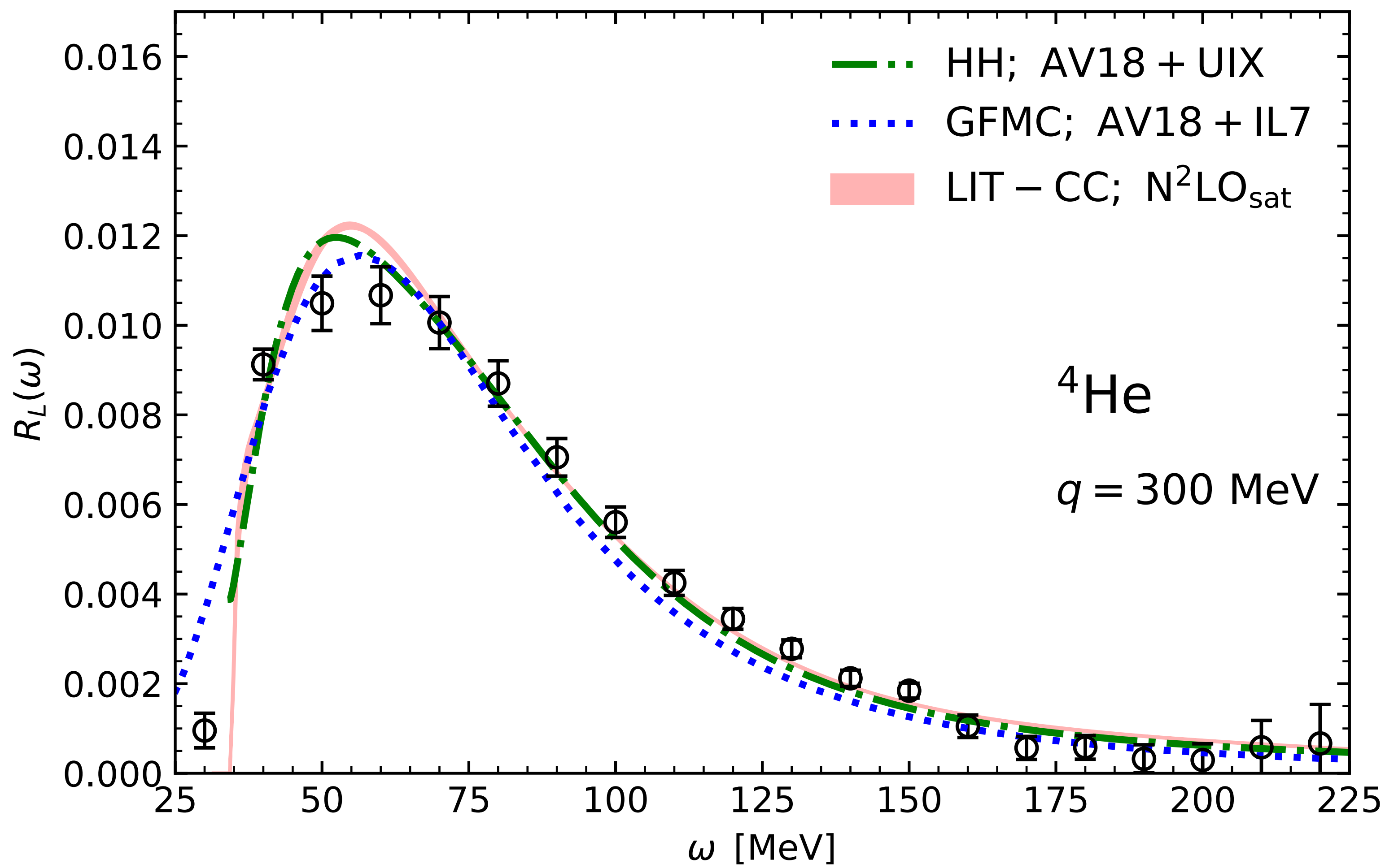
- Momentum transfer ~hundreds MeV
- Upper limit for ab initio methods
- Important mechanism for T2HK, DUNE
- Role of final state interactions
- Role of 1-body and 2-body currents

First step: analyse the longitudinal response for **electron scattering**

$$\left.\frac{d\sigma}{d\omega dq}\right|_e = \sigma_M\Big(\upsilon_L R_L + \upsilon_T R_T\Big)$$

charge operator $\hat{\rho}(q) = \sum_{j=1}^{Z} e^{iqz'_j}$

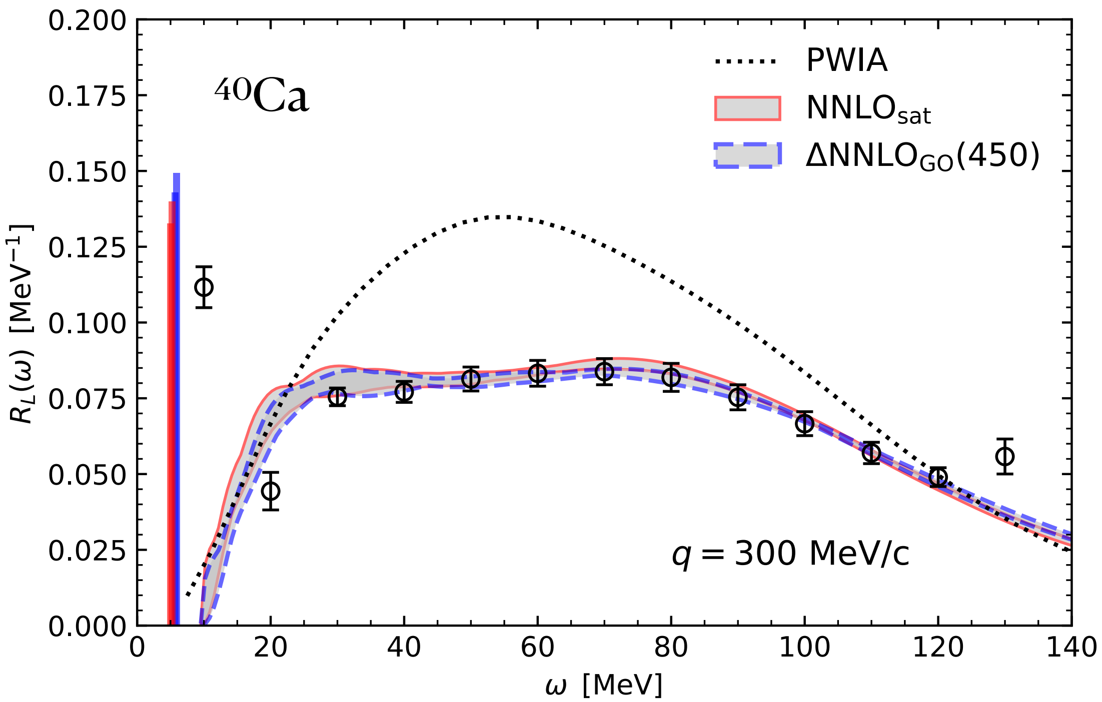
Longitudinal response

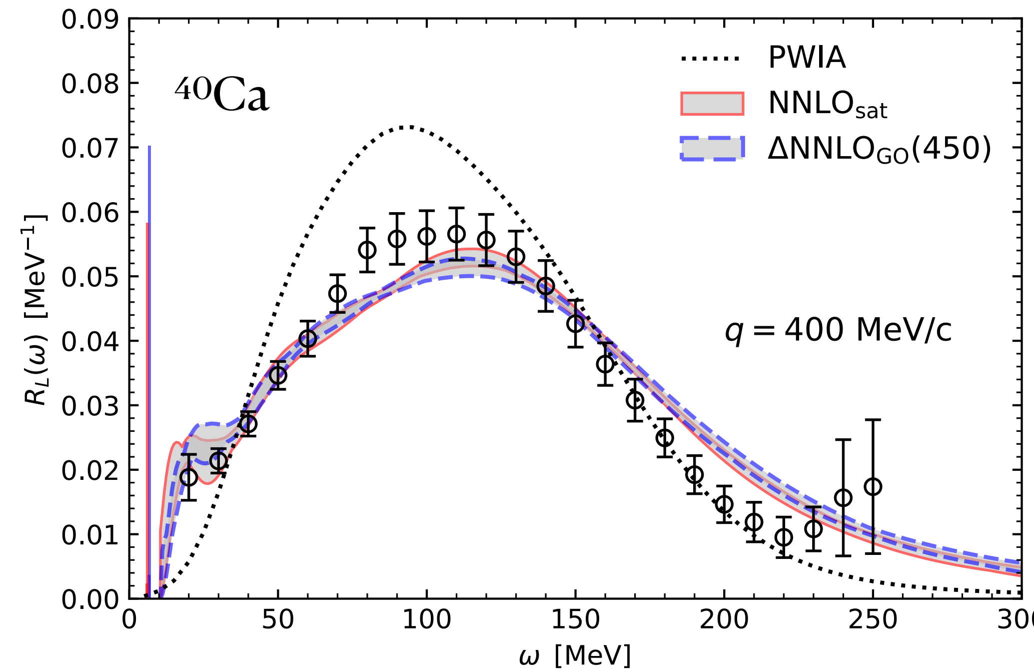


Uncertainty band: inversion procedure

$$R_{\mu\nu}(\omega, q) = \sum\!\!\!\!\!\!\int_f \langle \Psi | J_\mu^\dagger | \Psi_f \rangle \langle \Psi_f | J_\nu | \Psi \rangle \delta(E_0 + \omega - E_f)$$

Longitudinal response

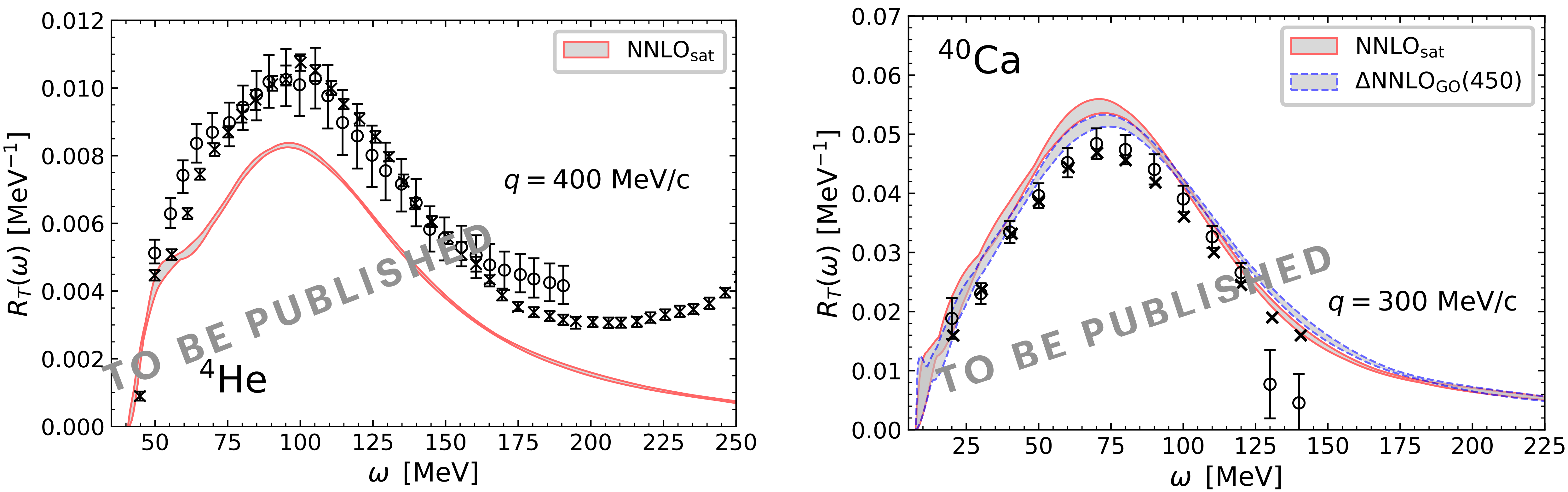




PRL 127 (2021) 7, 072501 JES, B. Acharya, S. Bacca, G. Hagen

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

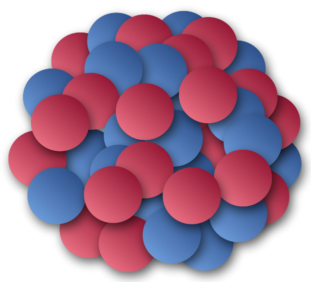
Transverse response



➡ This allows to predict electron-nucleus cross-section

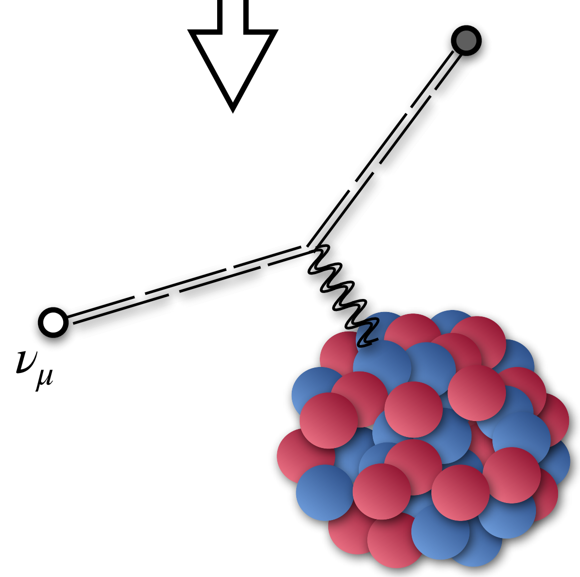
➡ Currently only 1-body current

Low/high energies



$$\hat{H}\,|\psi_A\rangle = E\,|\psi_A\rangle$$

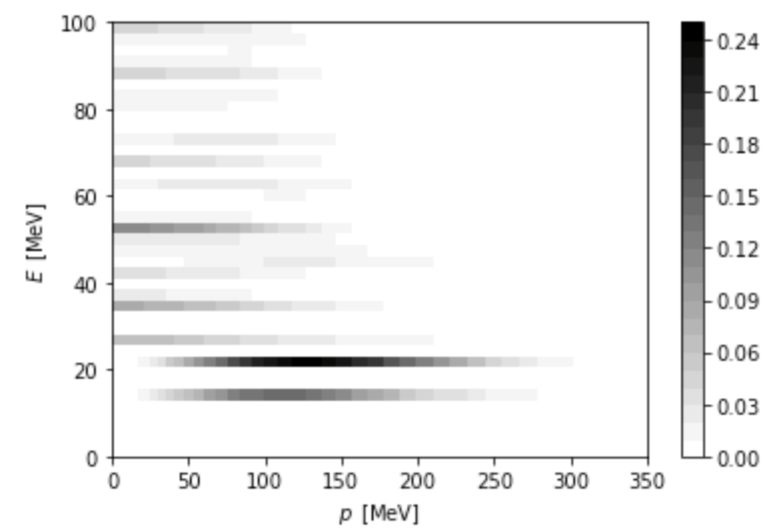
Many-body problem



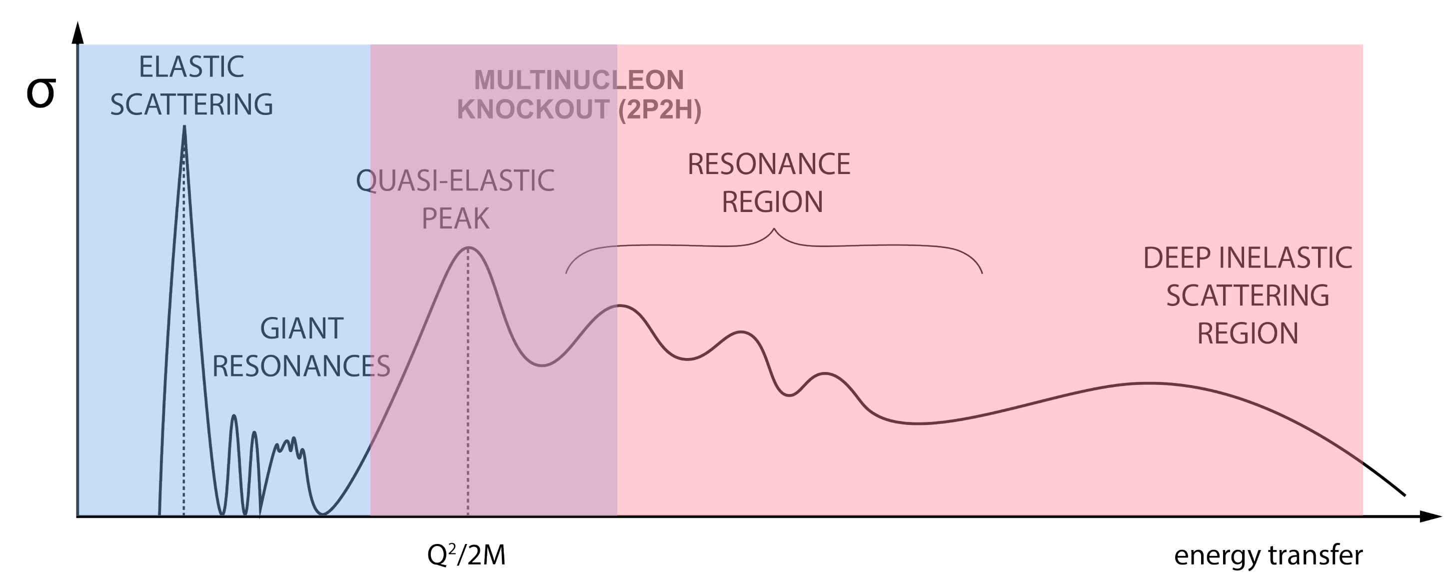
$$\langle \psi_f |\, \hat{j}\, | \psi_A \rangle$$

Electroweak responses

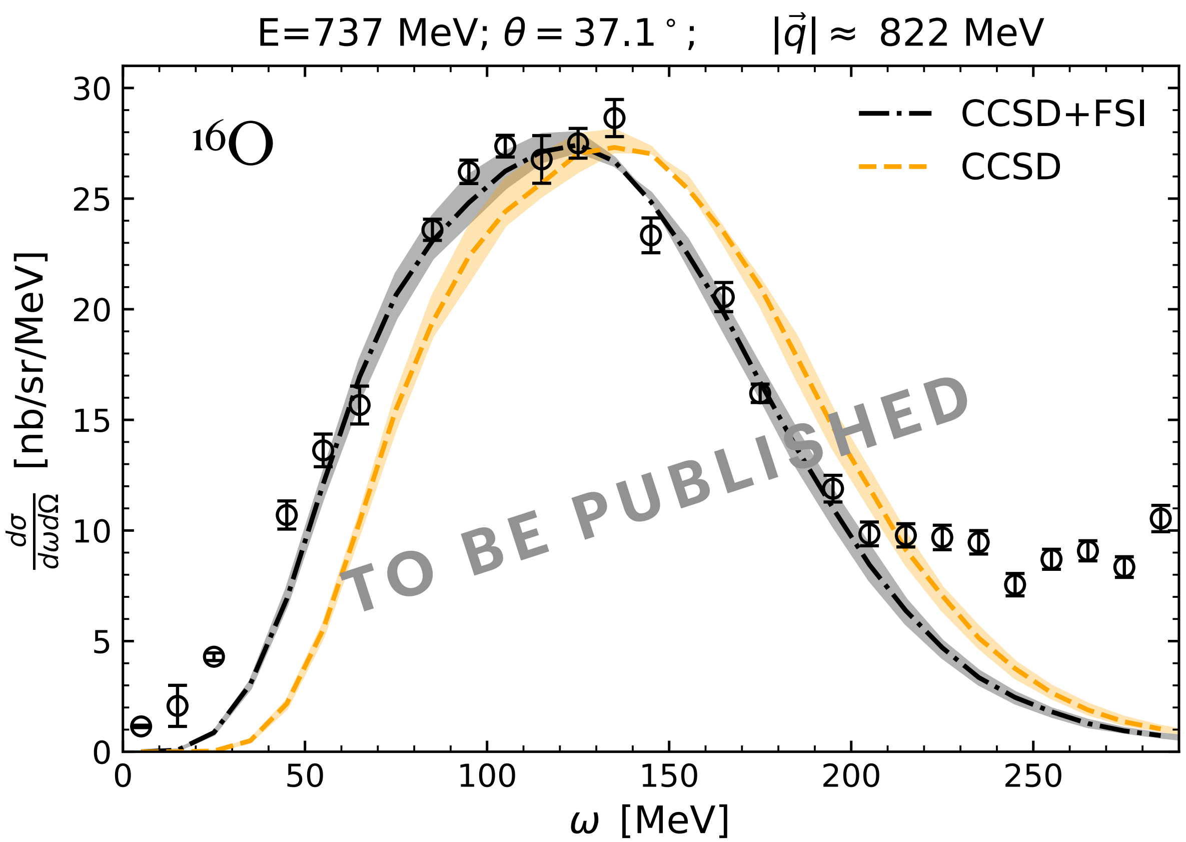
Spectral function

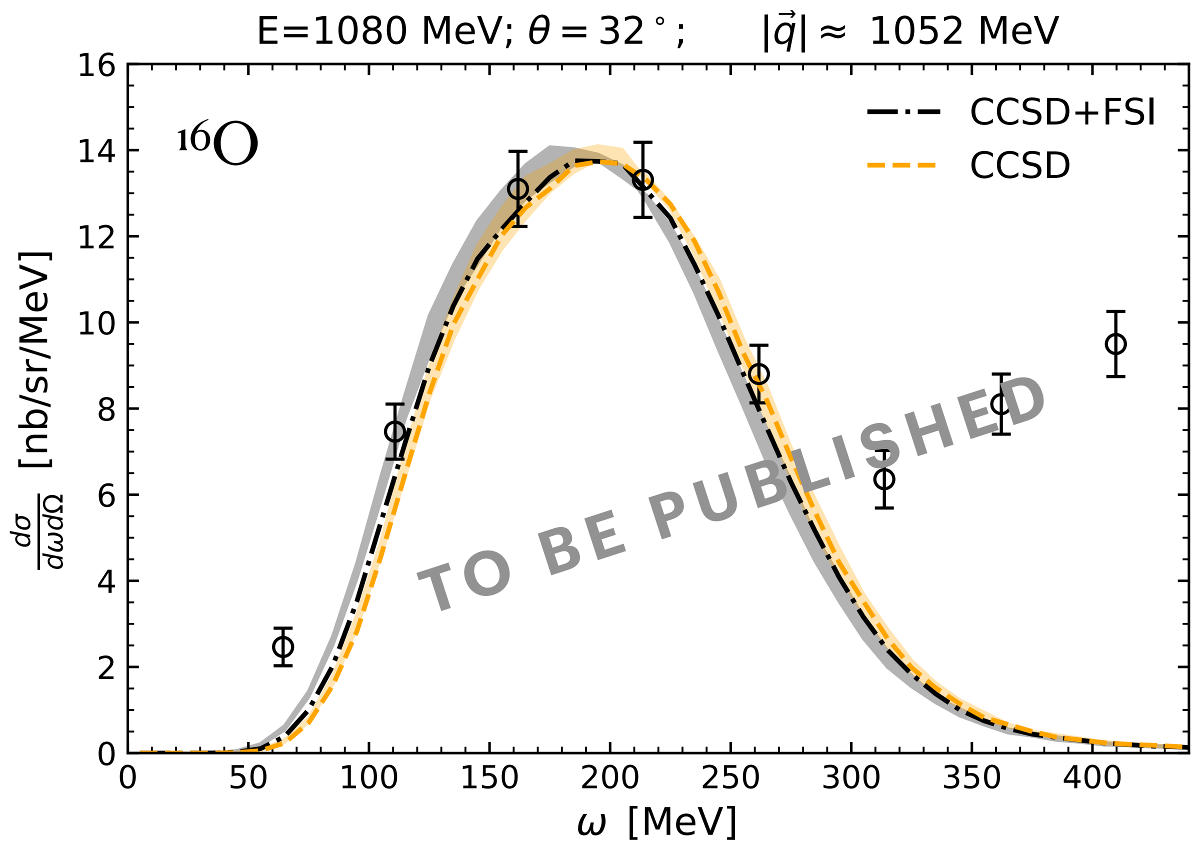


Probability density of finding nucleon $(E, \mathbf{p})$ in ground state nucleus



Spectral function from coupled cluster

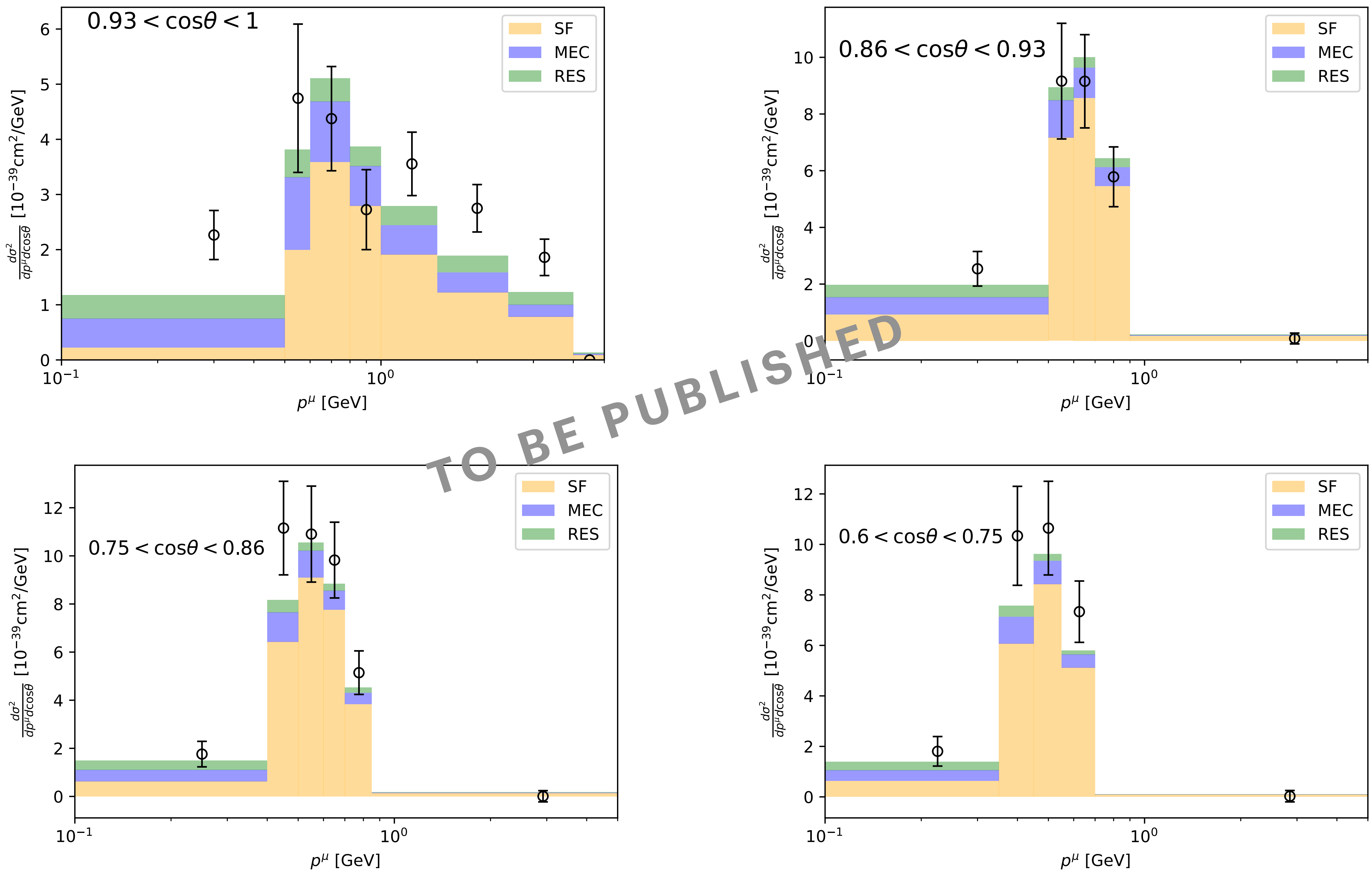




JES et al, in preparation (2022)

Spectral function from coupled cluster

Data: Phys. Rev. D 101, 112004 (2020)



JES et al, in preparation (2022)

Summary & Outlook

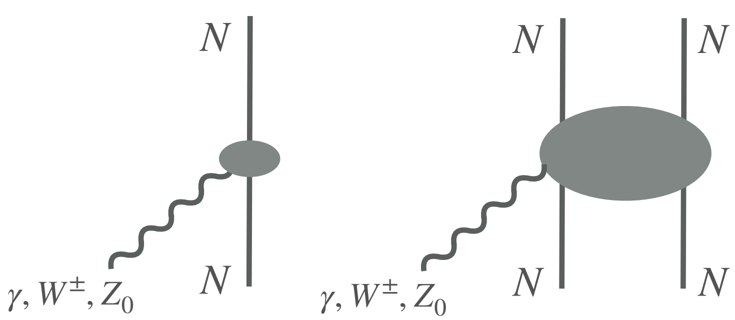
- Nuclear ab initio methods: connection to underlying QCD through chiral hamiltonians & uncertainty control
- First results from the coupled cluster theory: on the way to obtain cross-section for neutrino scattering on medium-mass nuclei
- With **spectral functions** we gain direct impact on the experimental analysis (through Monte Carlo event generators used by experimental collaboration)

Thank you for attention!

Back up

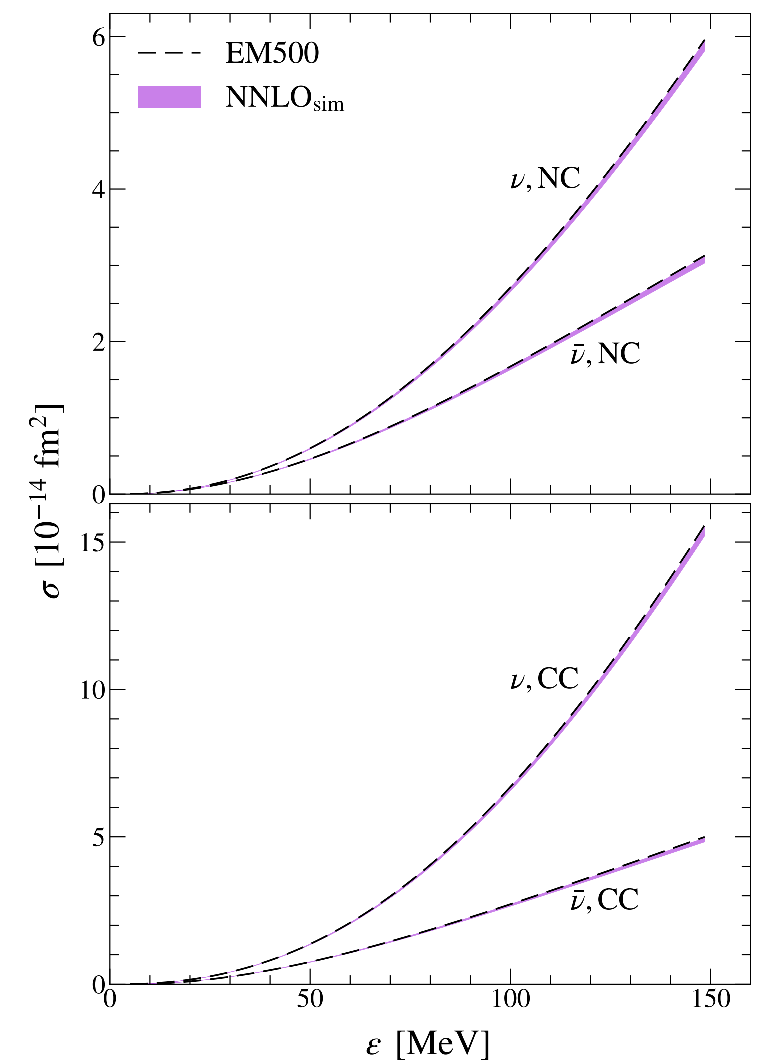
Electroweak currents

$$J = \sum_i j_i + \sum_{i<j} j_{ij} + \dots$$



known to give significant contribution for neutrino-nucleus scattering

$$\nu(\bar{\nu}) + d \to \mu^{\pm} + X$$



Current decomposition into multipoles needed for various *ab initio* methods: CC, No Core Shell Model, In-Medium Similarity Renormalization Group

Multipole decomposition for 1- and 2-body EW currents

B. Acharya, S. Bacca
Phys.Rev.C 101 (2020) 1, 015505

Lorentz Integral Transform

$$R_{\mu\nu}(\omega, q) = \sum_f \langle \Psi | J_\mu^\dagger | \Psi_f \rangle \langle \Psi_f | J_\nu | \Psi \rangle \delta(E_0 + \omega - E_f)$$

continuum spectrum

Instead we calculate

$$S_{\mu\nu}(\omega, q) = \int d\sigma K(\omega, \sigma) R_{\mu\nu}(\omega, q) = \int d\sigma \langle \Psi | J_\mu^\dagger \, K(\mathscr{H} - E_0, \sigma) \, J_\nu | \Psi \rangle$$

$S_{\mu\nu}$ has to be inverted to get access to $R_{\mu\nu}$

Lorentzian kernel:

$$K_\Lambda(\omega, \sigma) = \frac{1}{\pi} \frac{\Lambda}{\Lambda^2 + (\omega - \sigma)^2}$$

➡ LIT-CC used for photo-absorption

Electrons for neutrinos

$$\left.\frac{d\sigma}{d\omega dq}\right|_{\nu/\bar{\nu}} = \sigma_0\left(v_{CC}R_{CC} + v_{CL}R_{CL} + v_{LL}R_{LL} + v_T R_T \pm v_{T'}R_{T'}\right)$$

$$\left.\frac{d\sigma}{d\omega dq}\right|_{e} = \sigma_M\left(v_L R_L + v_T R_T\right)$$

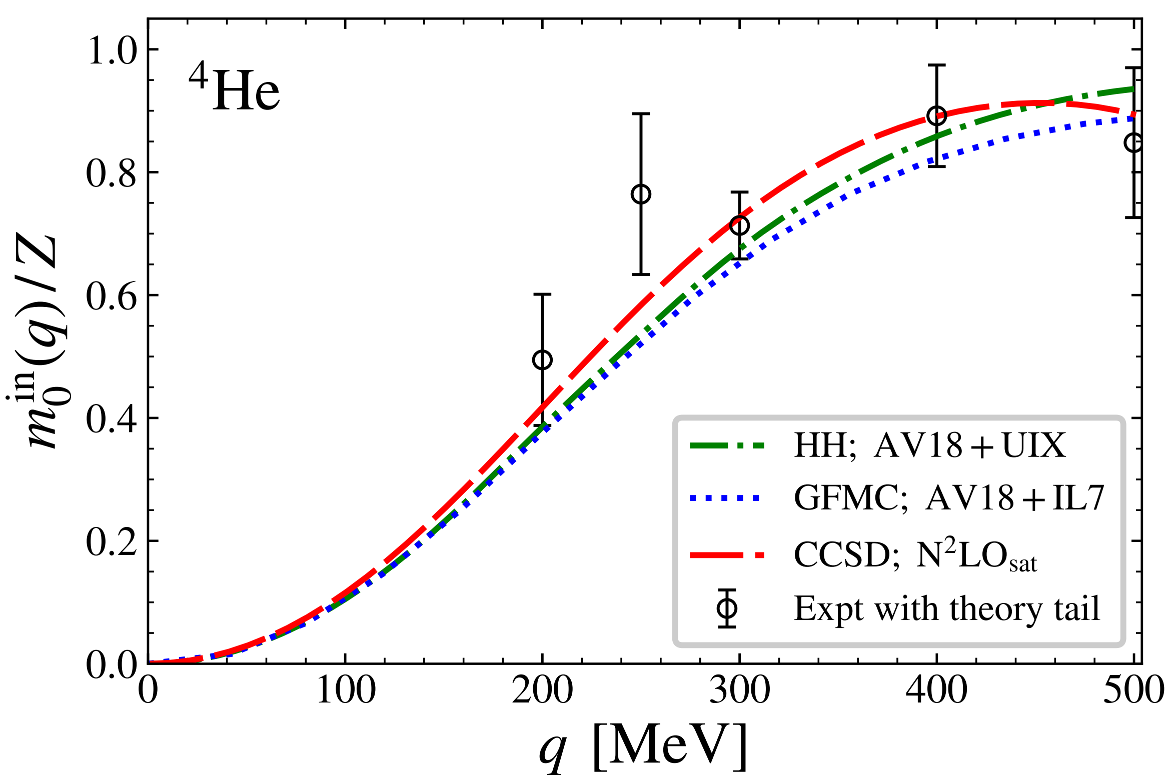
✓ much more precise data

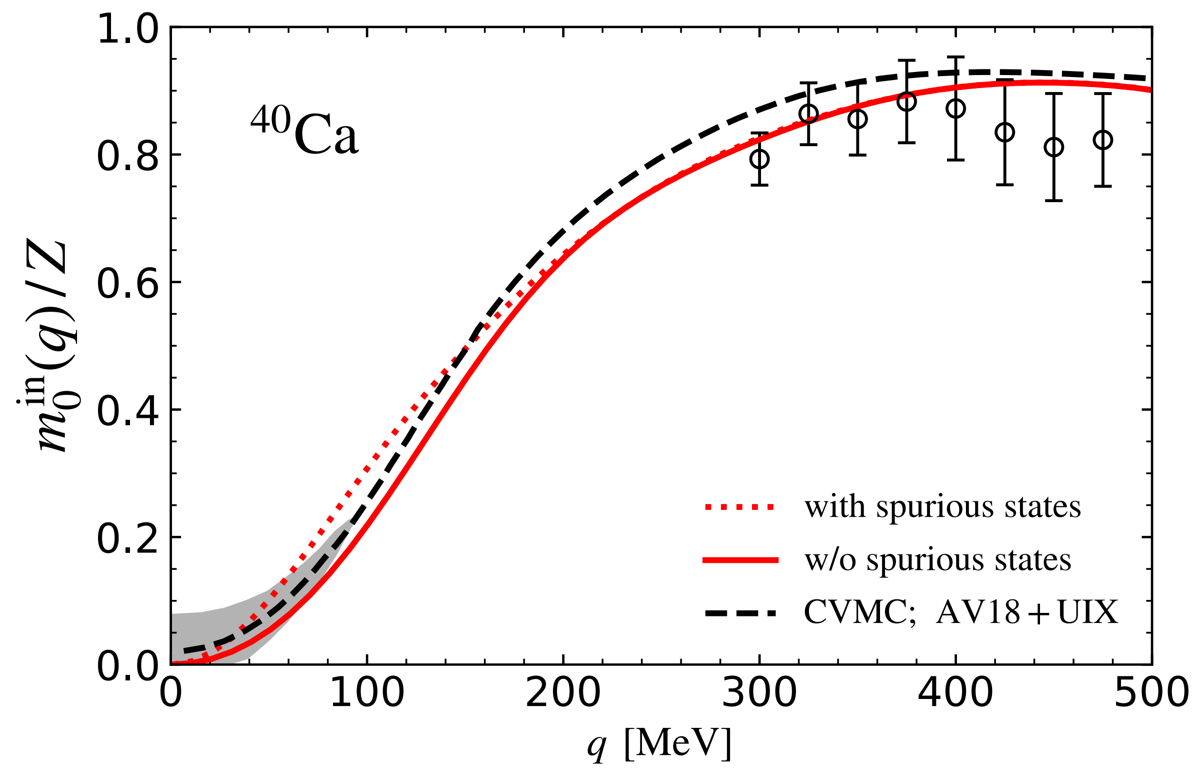
✓ we can get access to R_L and R_T separately (Rosenbluth separation)

✓ experimental programs of electron scattering in JLab, MESA

Coulomb sum rule

$$m_0(q) = \int d\omega R_L(\omega, q) = \sum_{f \neq 0} |\langle \Psi_f | \hat{\rho} | \Psi \rangle|^2 = \langle \Psi | \hat{\rho}^\dagger \hat{\rho} | \Psi \rangle - |F_{el}(q)|^2$$

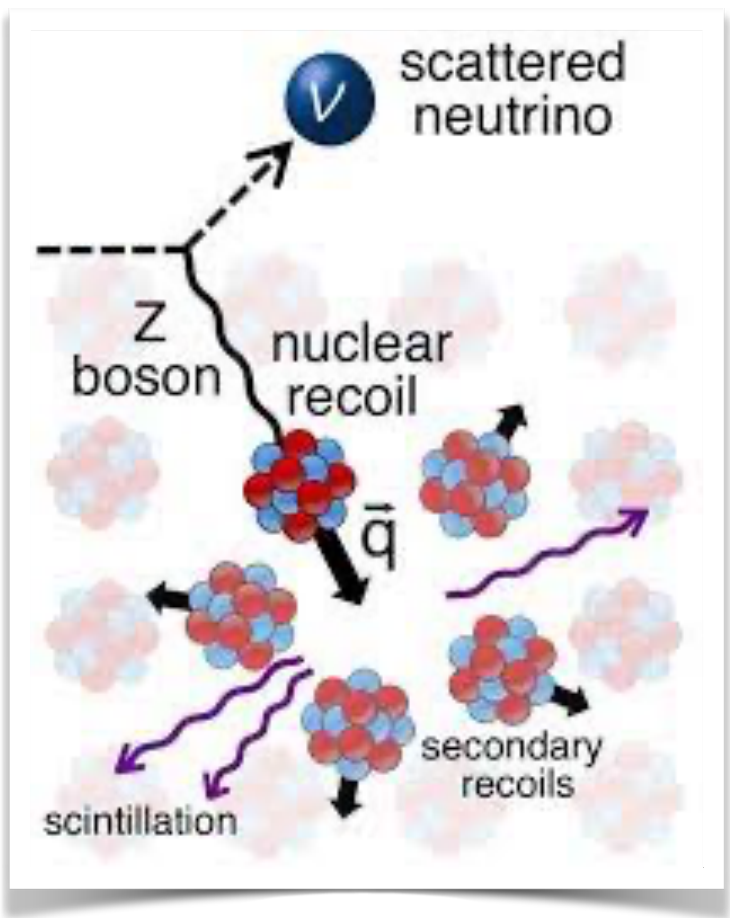


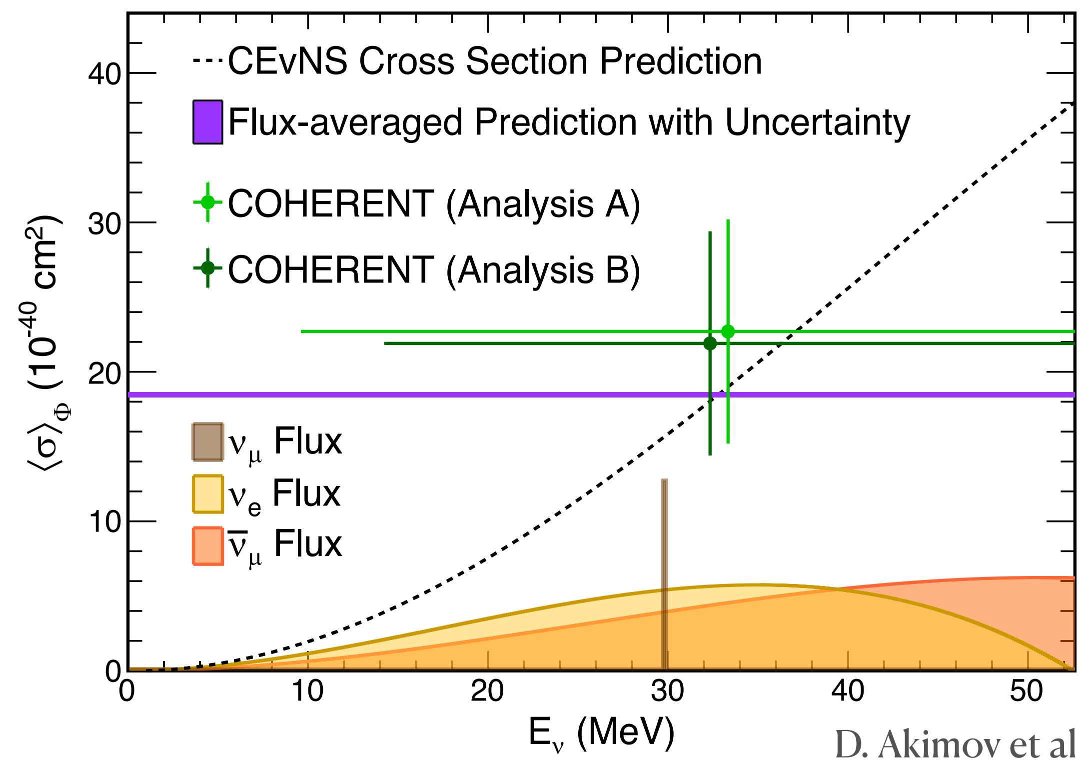


JES, B. Acharya, S.Bacca, G. Hagen Phys.Rev.C 102 (2020) 064312

PRL 127 (2021) 7, 072501 JES, B. Acharya, S. Bacca, G. Hagen

CEvNS on ^{40}Ar





D. Akimov et al
PRL 126 (2021) 012002

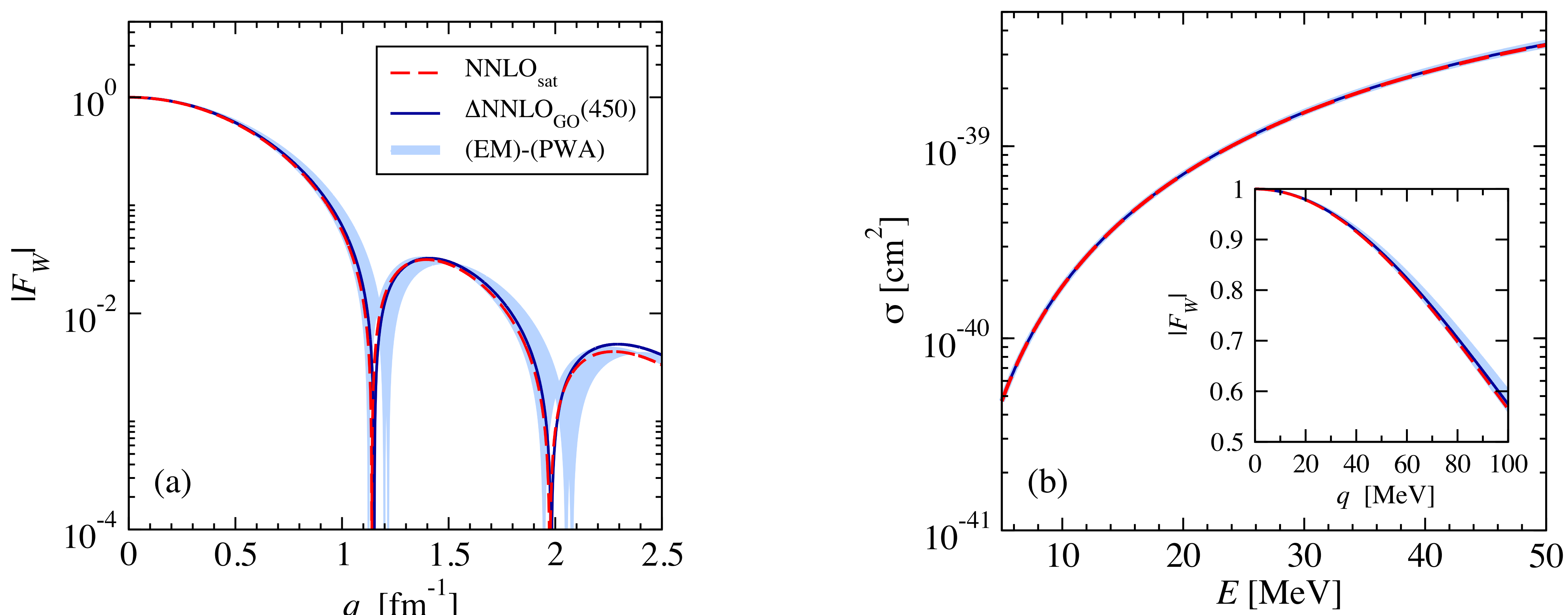
$$\frac{d\sigma}{dT}(E_\nu, T) \simeq \frac{G_F^2}{4\pi} M \left[1 - \frac{MT}{2E_n u^2}\right] Q_W^2 F_W^2(q^2) \propto N^2 \qquad Q_W = N - (1 - 4\sin^2\theta_W)Z$$

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

Nuclear weak form-factor

CEvNS on ^{40}Ar

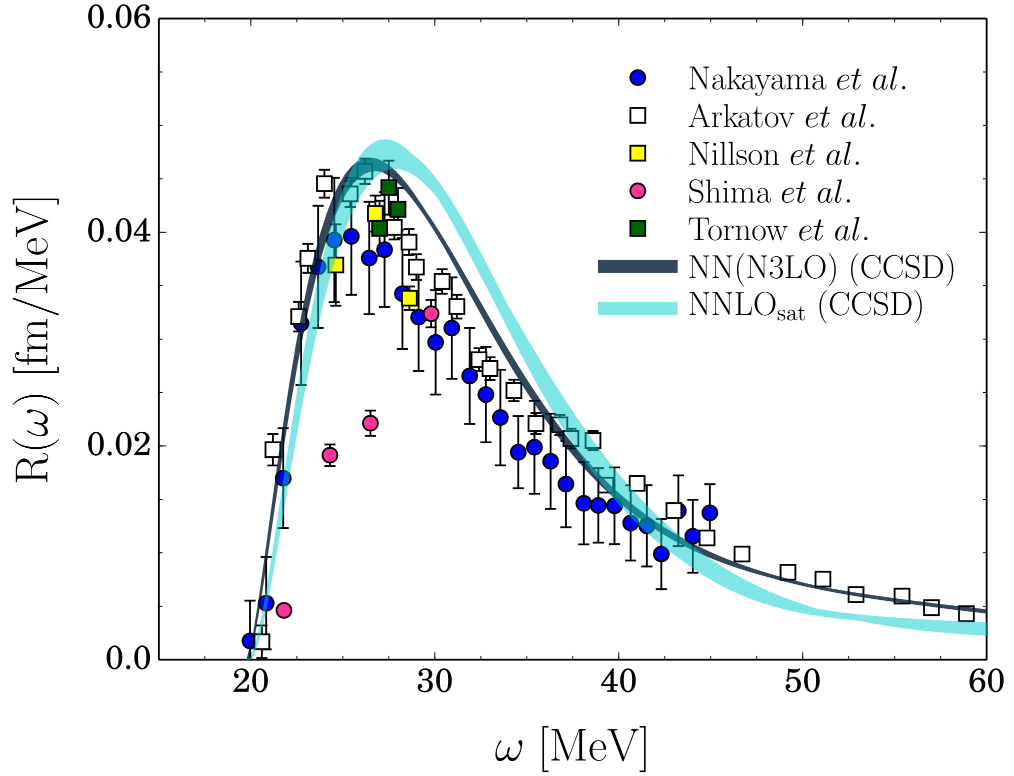
$$F_W(q^2) = \frac{1}{Q_W}\left[NF_n(q^2) - (1 - 4\sin^2\theta_W)ZF_p(q^2)\right]$$



C. Payne at al.
Phys.Rev.C 100 (2019) 6, 061304

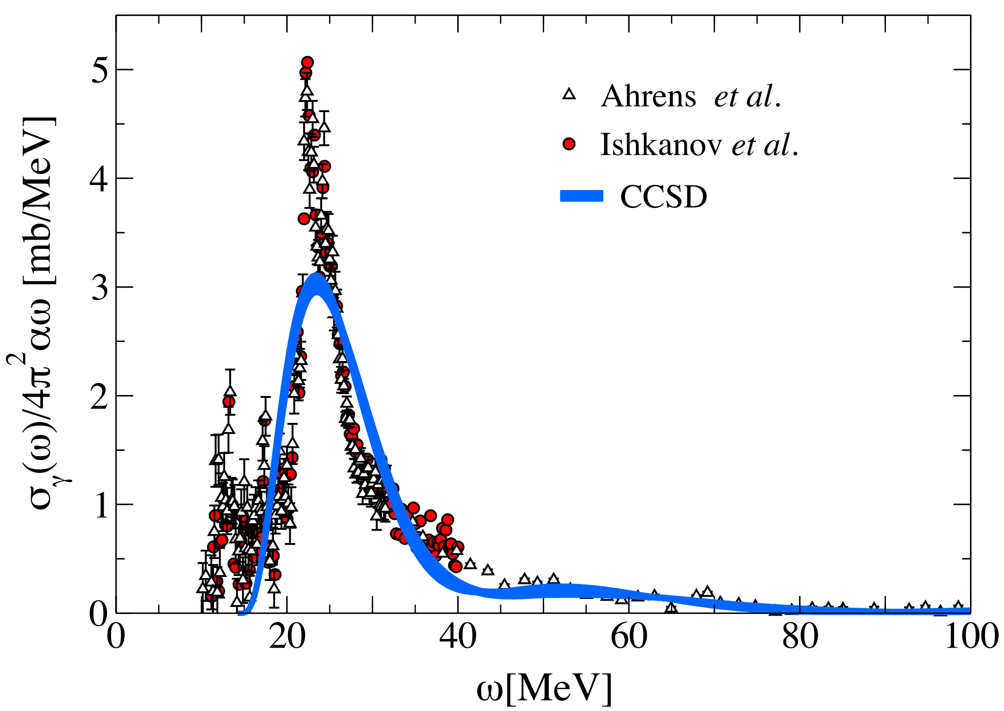
- Coupled-cluster predictions for the weak form factor and cross section
- Small theoretical uncertainty

LIT-CC method



M. Miorelli et al.
Phys.Rev.C 94 (2016) 3, 034317

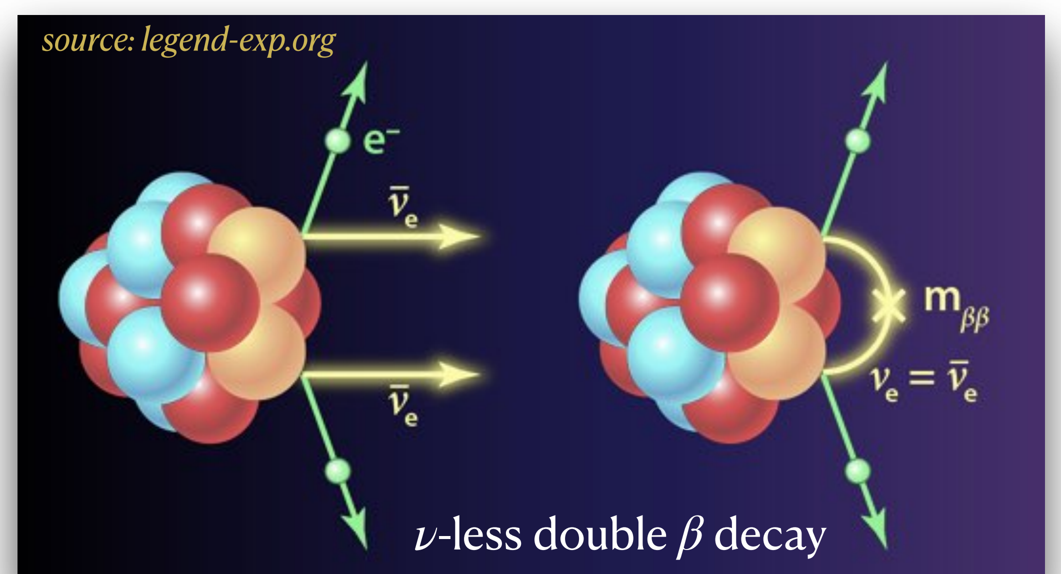
^{4}He photo-absorption

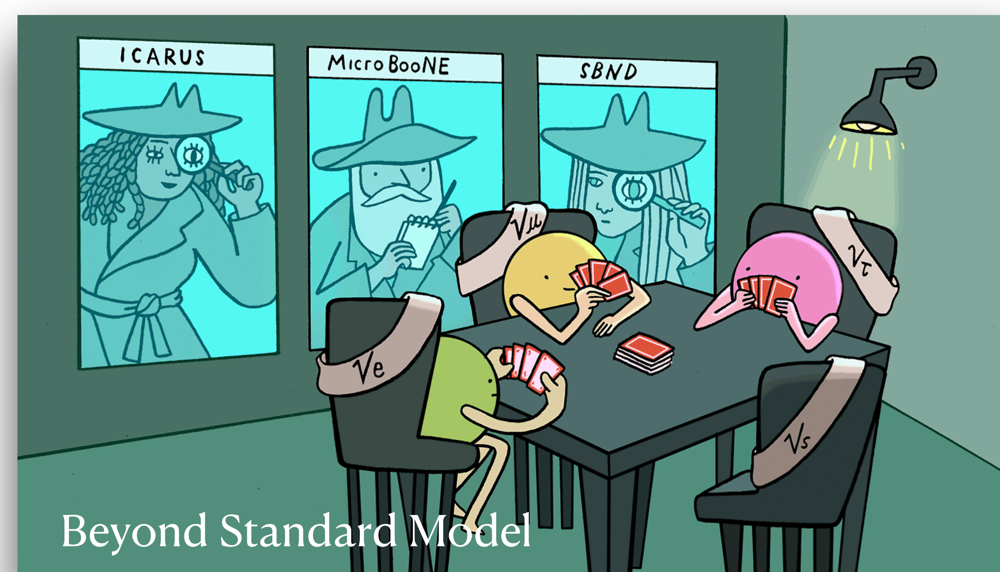


S. Bacca et al.
Phys.Rev.C 90 (2014) 6, 064619

giant dipole resonance in ^{16}O

Motivation





source: symmetrymagazin.org