Electron data for neutrino scattering cross sections

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QNP2022, 6 September 2022

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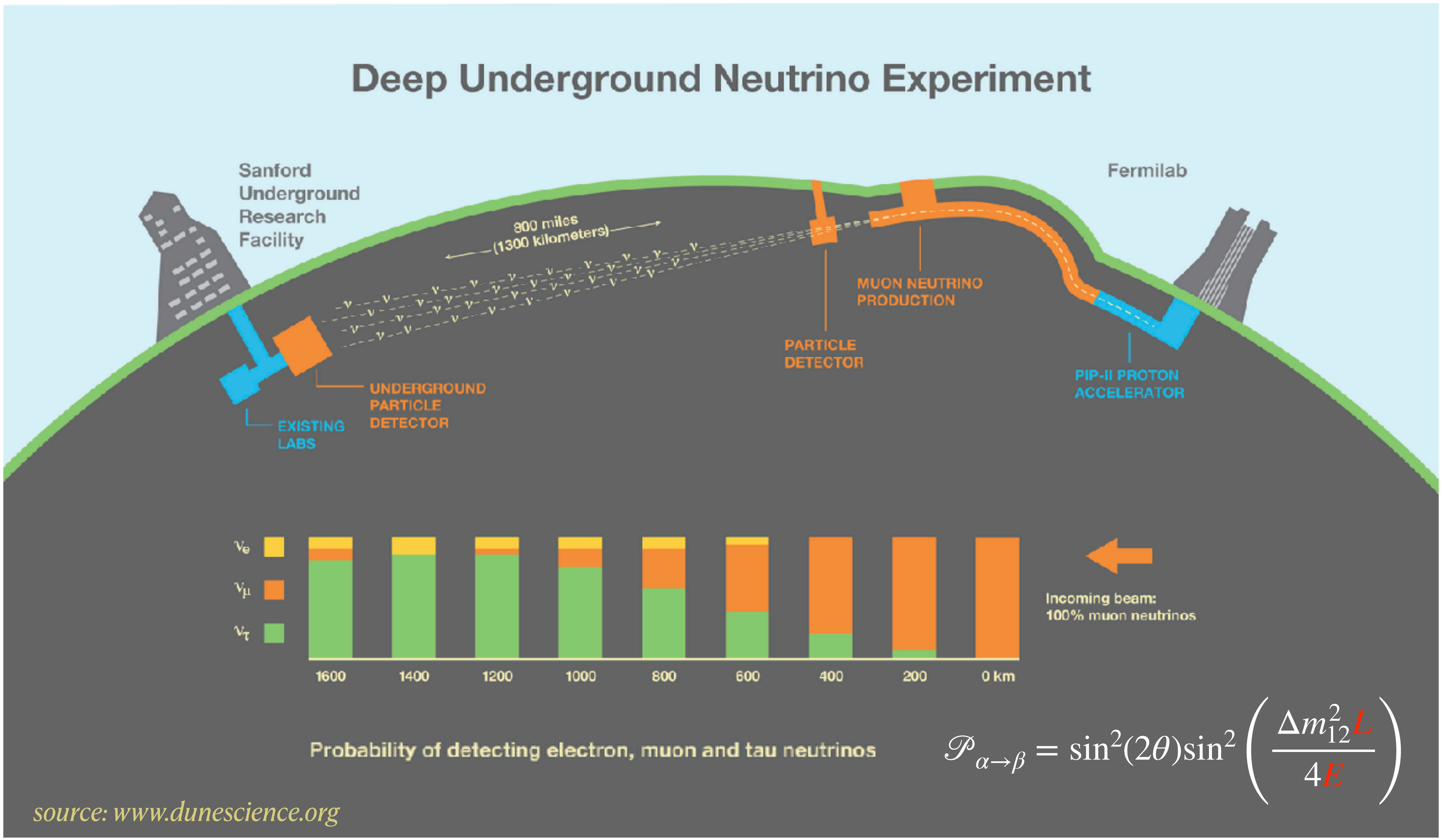
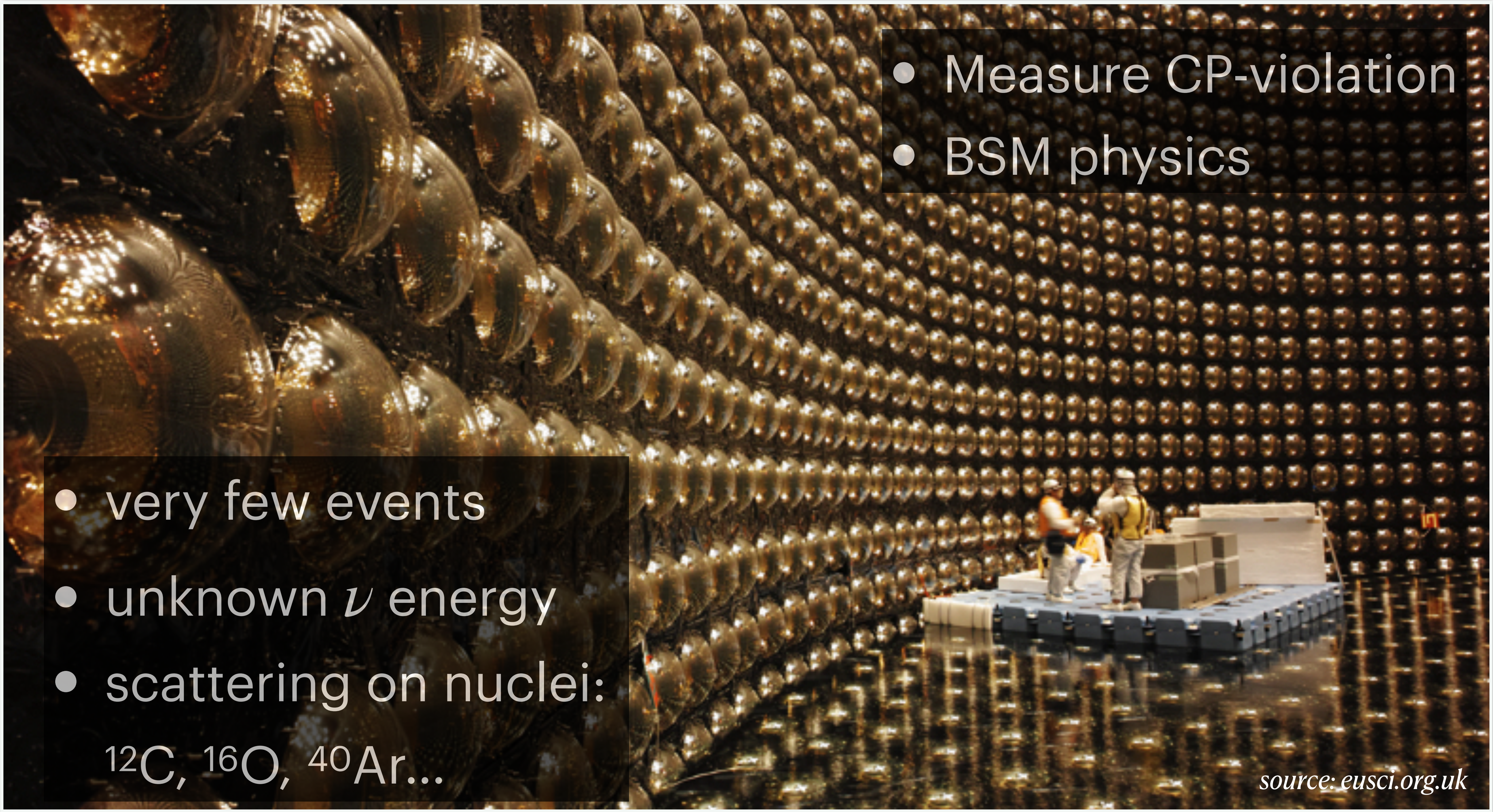
Neutrino oscillations

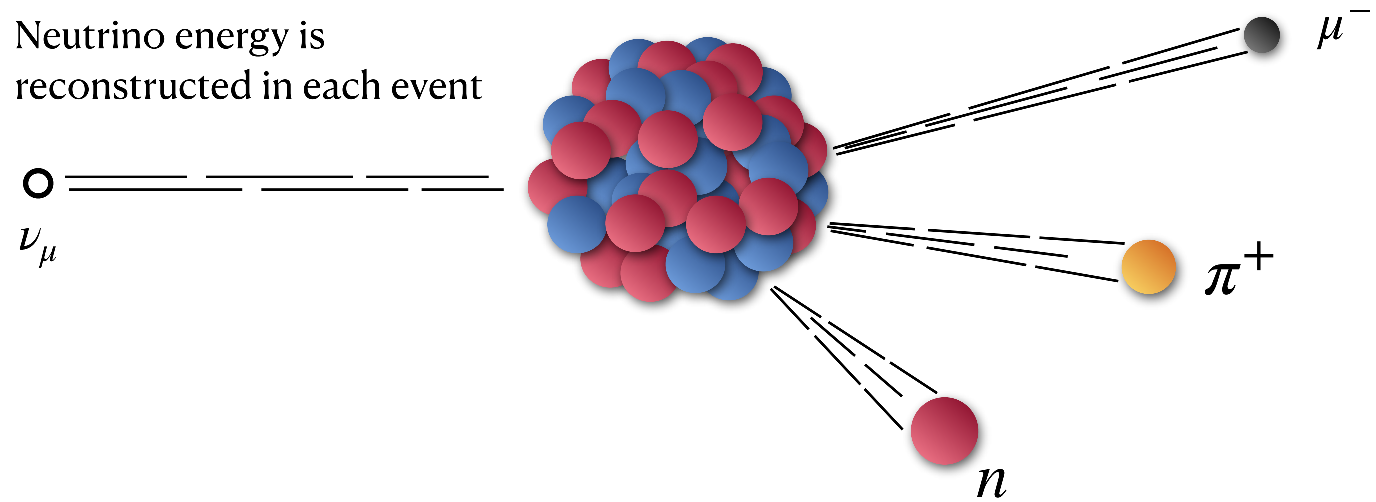


$$\mathscr{P}_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)$$

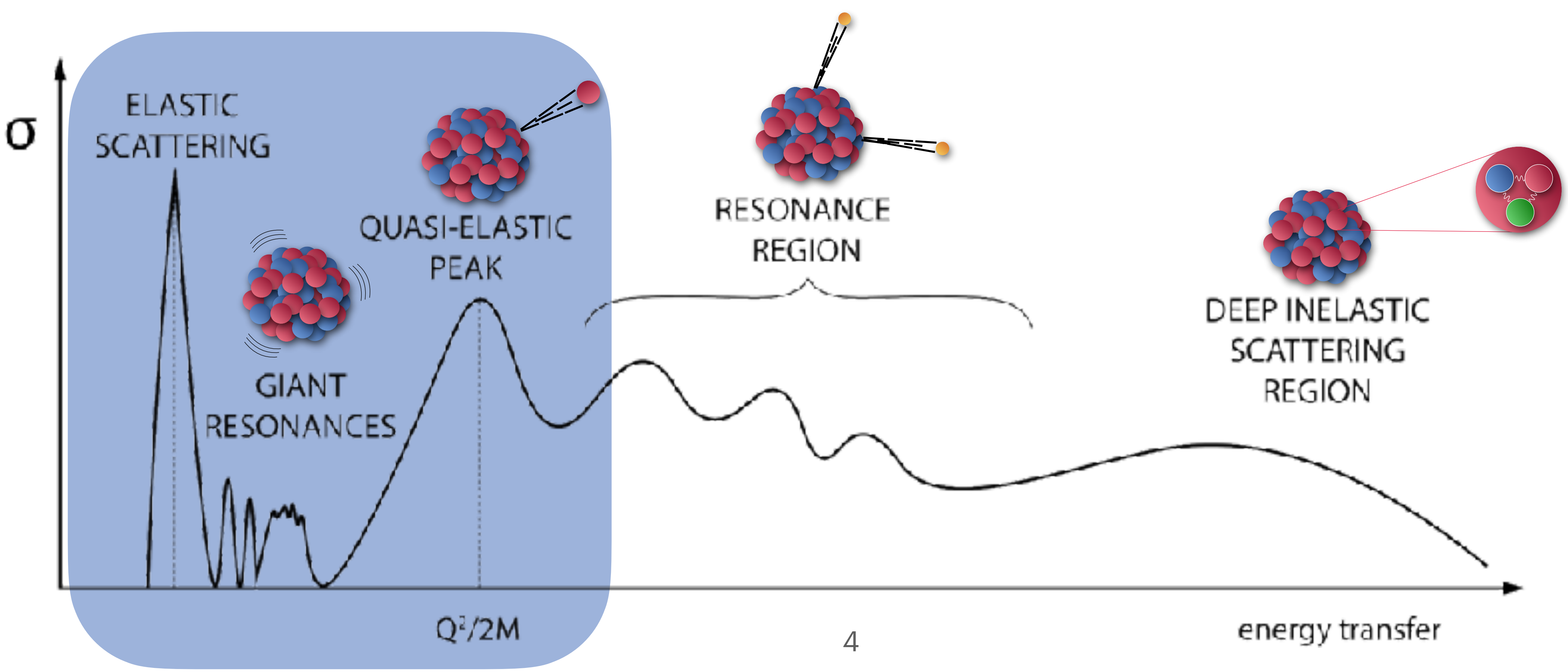
Aims & challenges



Motivation

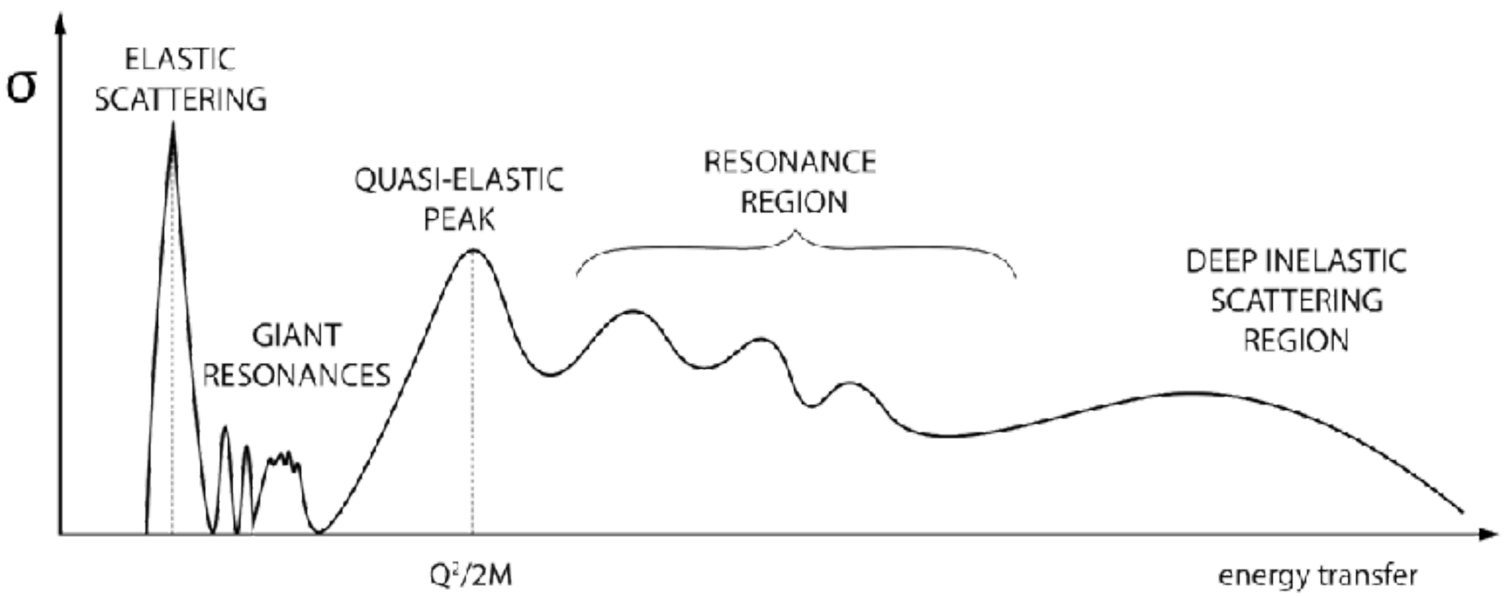


Neutrino energy is
reconstructed in each event
ν_μ
μ^-
π^+
n



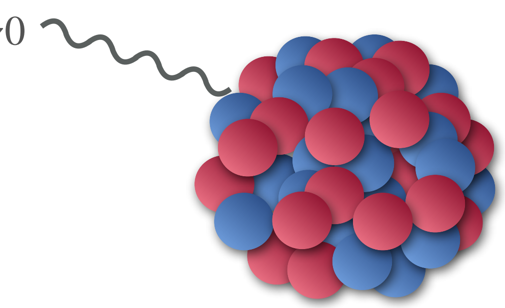
σ
ELASTIC
SCATTERING
GIANT
RESONANCES
QUASI-ELASTIC
PEAK
RESONANCE
REGION
DEEP INELASTIC
SCATTERING
REGION
Q²/2M
energy transfer

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

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

Electrons for neutrinos

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

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

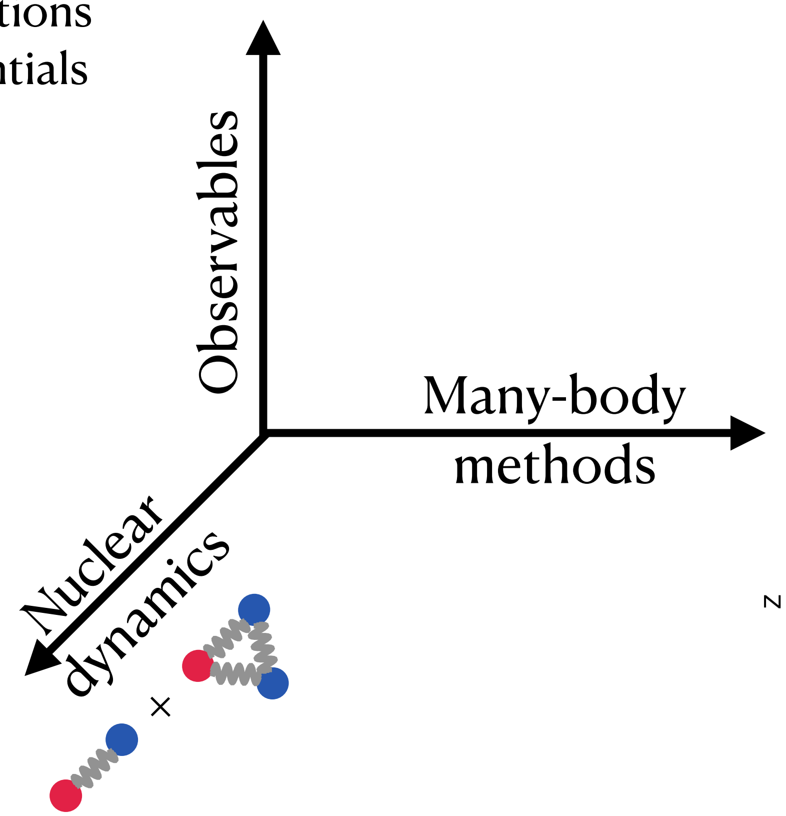
✓ much more precise data

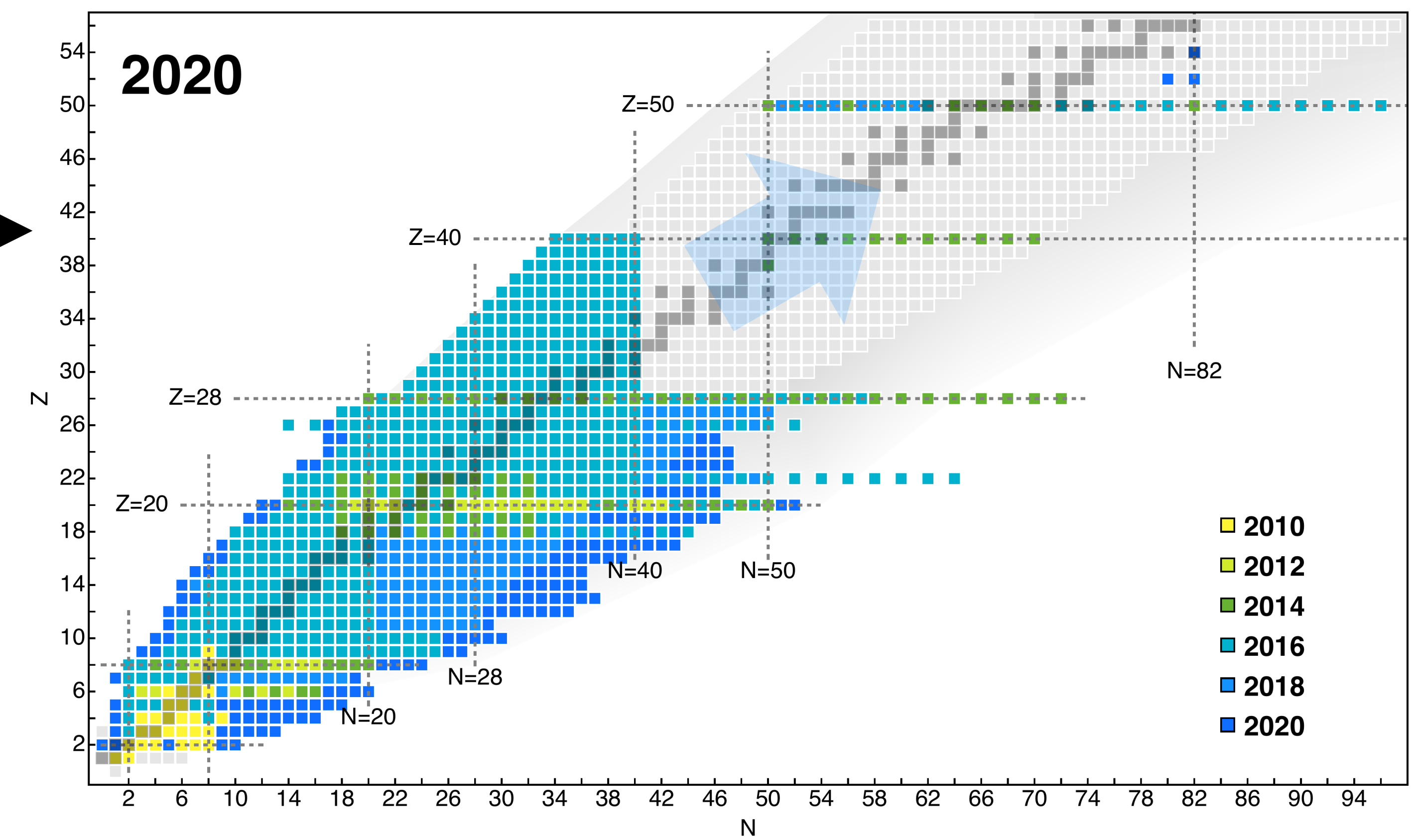
✓ we can get access to R_L and R_T separately (Rosenbluth separation)

✓ experimental programs of electron scattering in JLab, MAMI, MESA

Ab initio nuclear theory

➡ Nuclear responses
➡ Spectral functions
➡ Optical potentials
…

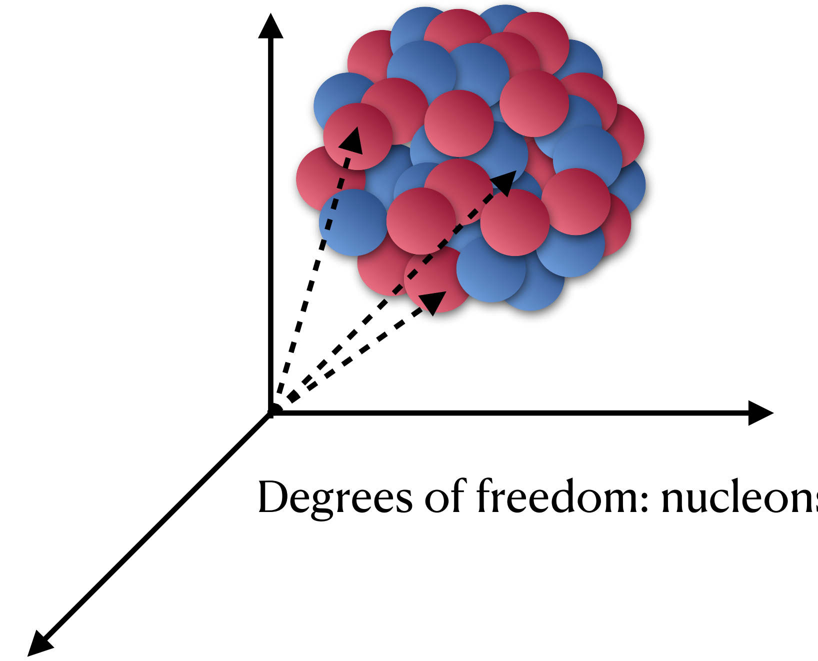




H. Hergert, *Front.in Phys.* 8 (2020) 379

➡ **Neutrinos challenge ab initio nuclear theory**
➡ **Controllable approximations within ab initial nuclear theory**

Ab initio nuclear theory for neutrinos



Nuclear Hamiltonian

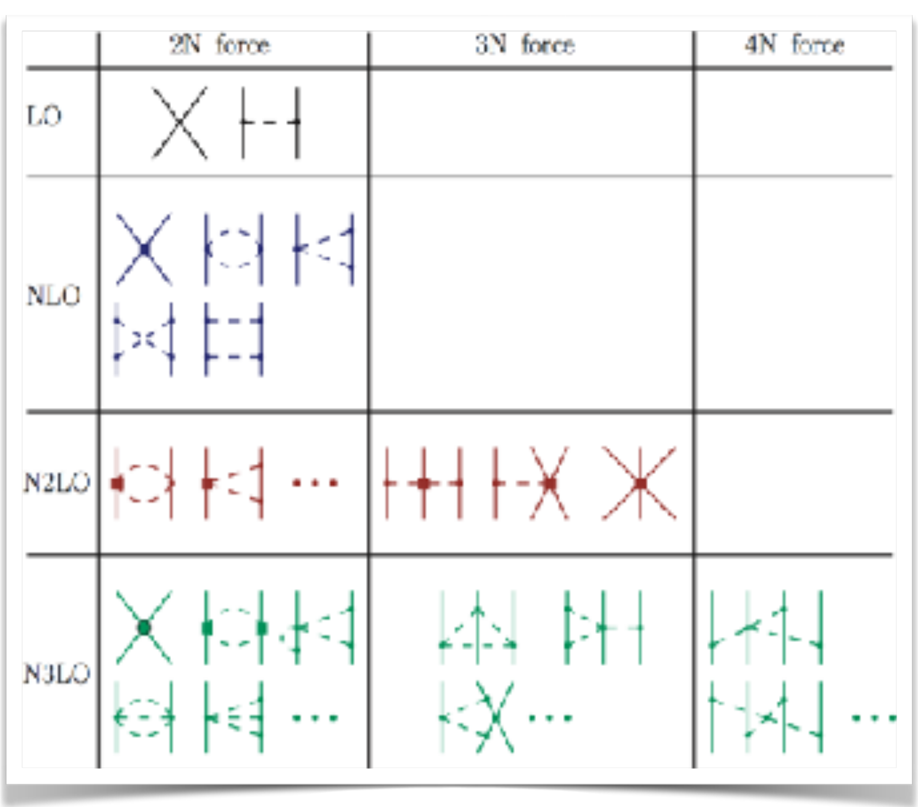
$$\mathscr{H}\,|\Psi\rangle = E\,|\Psi\rangle$$

$n = 0$

$n = 2$

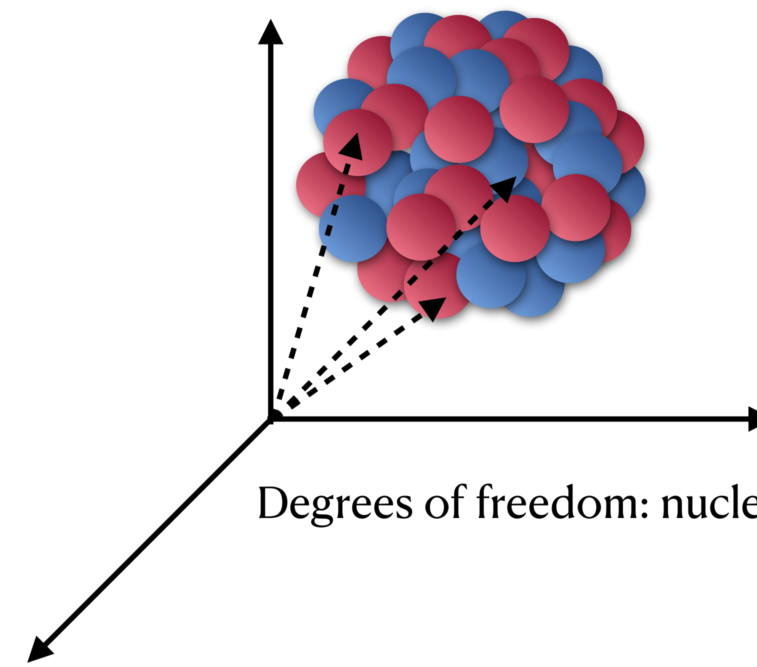
$n = 3$

$n = 4$



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

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

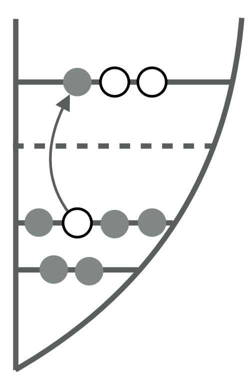
similarity transformed Hamiltonian (non-Hermitian)

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

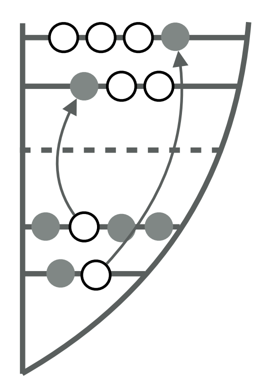
Expansion: $T = \sum t_a^i a_a^\dagger a_i + \sum t_{ab}^{ij} a_a^\dagger a_b^\dagger a_i a_j + \dots$

←coefficients obtained through coupled cluster equations

singles



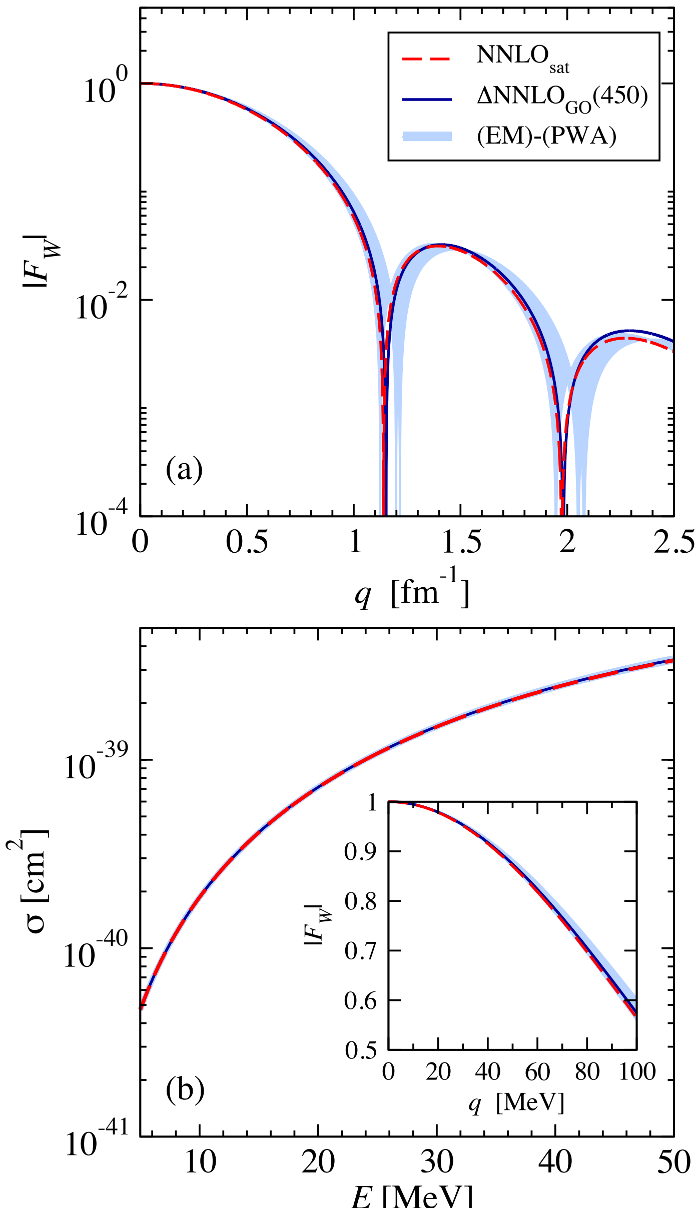
doubles



Coupled cluster method

- ✓ Controlled approximation through truncation in T
- ✓ Polynomial scaling with A (predictions for ^{100}Sn, ^{208}Pb)
- ✓ Works most efficiently for doubly magic nuclei

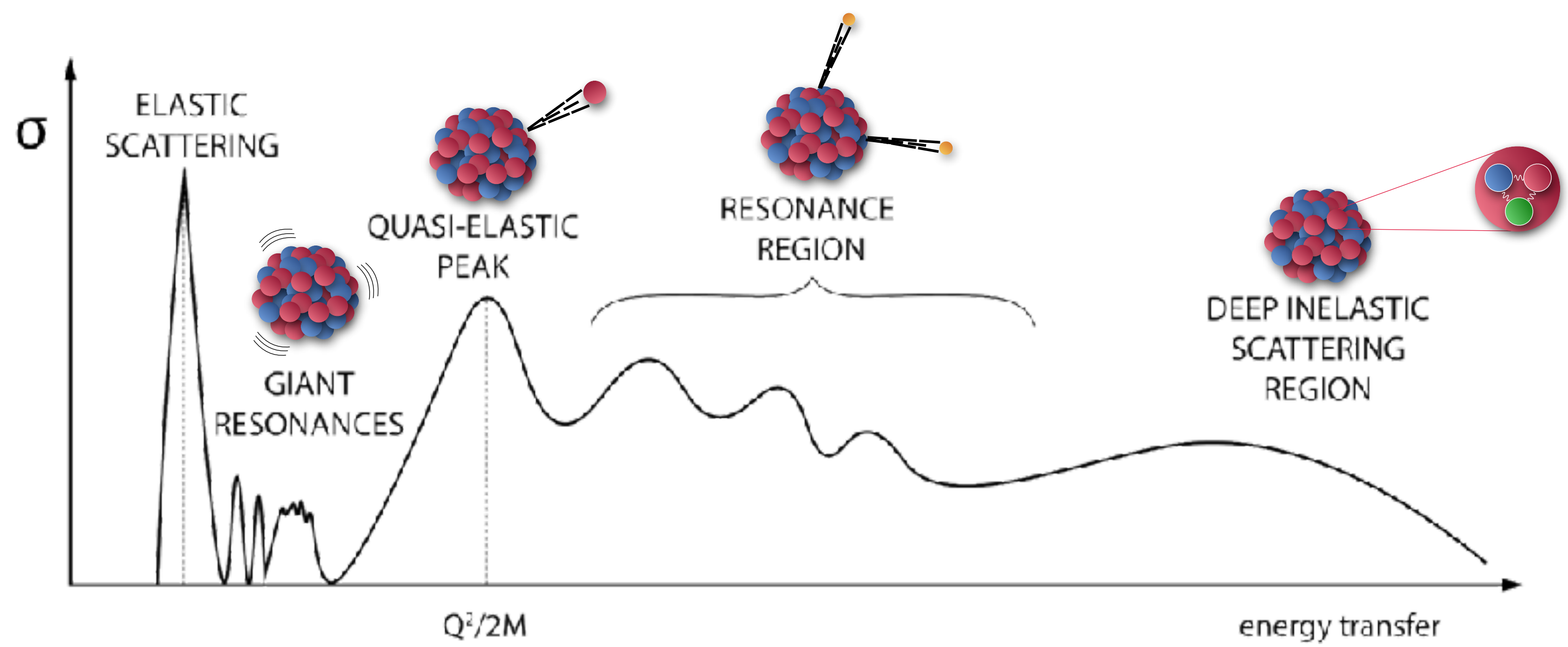
coherent elastic neutrino scattering on ^{40}Ar



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

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



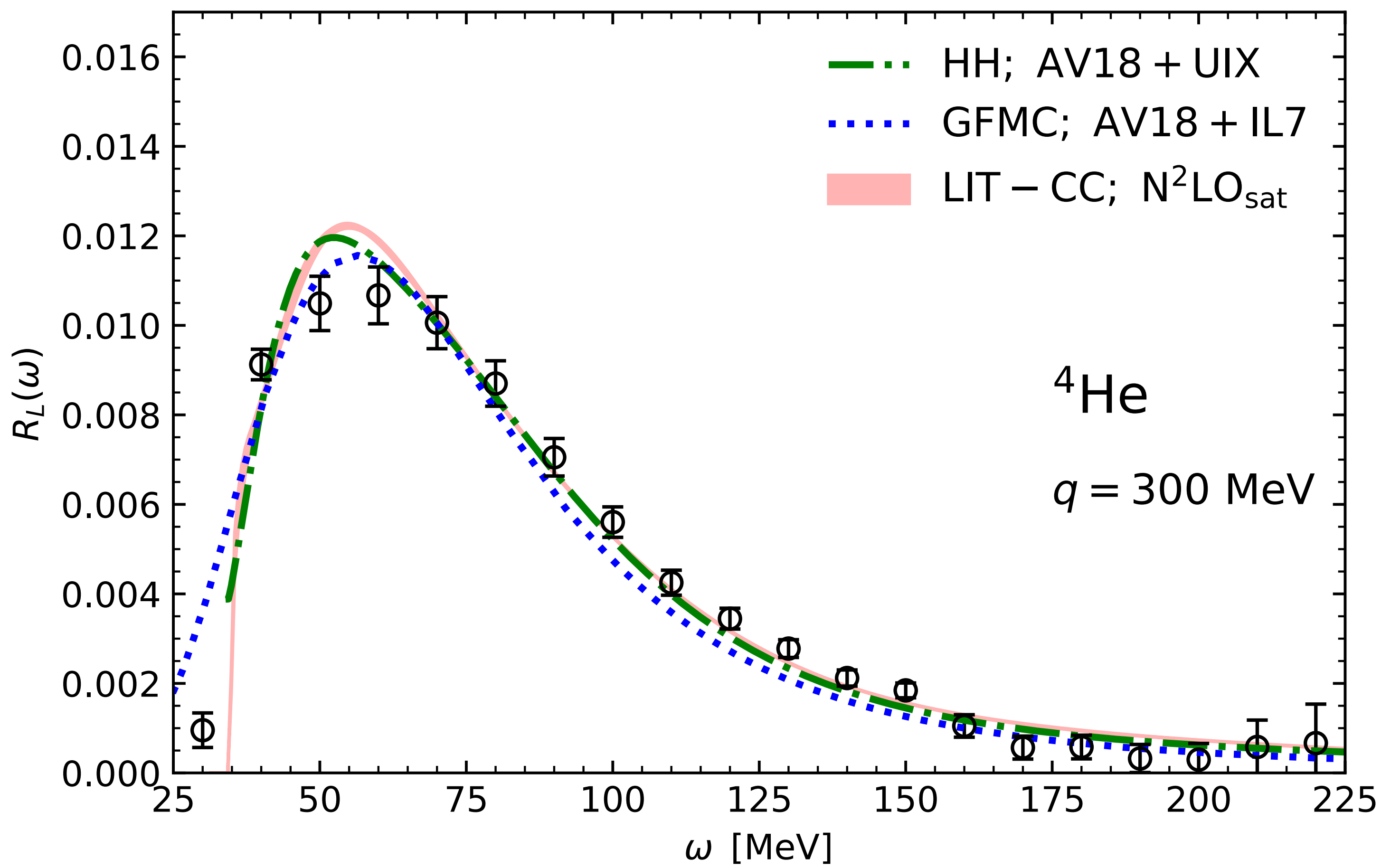
First step: analyse the longitudinal response

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

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

Longitudinal response

Lorentz Integral Transform + Coupled Cluster

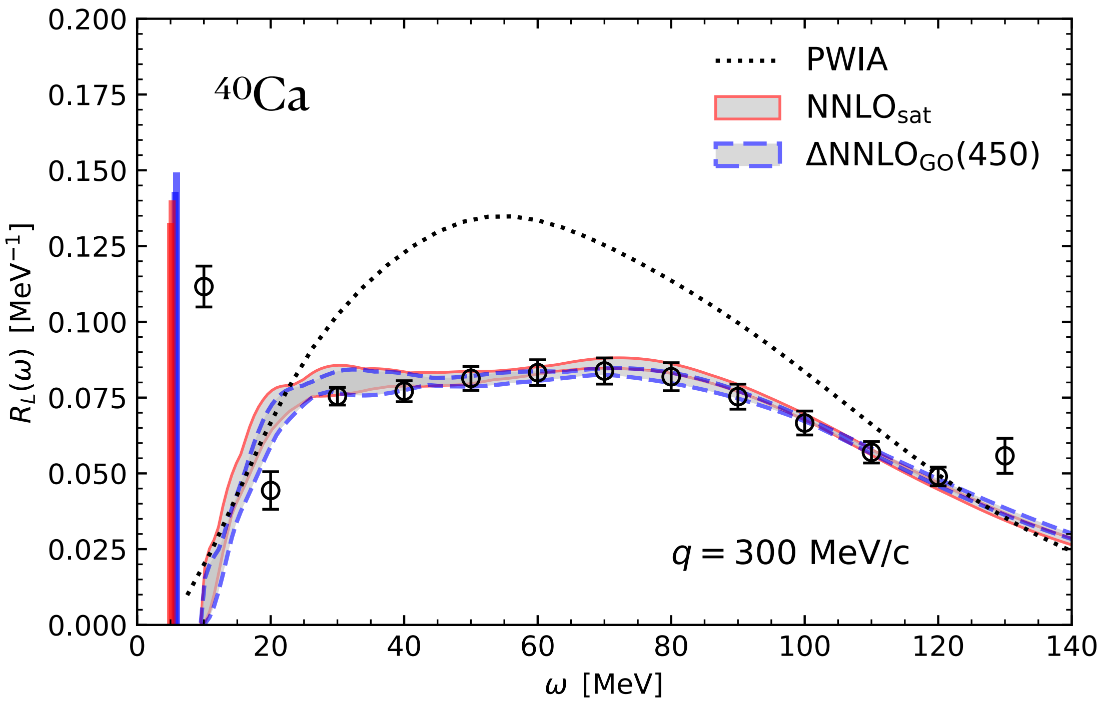


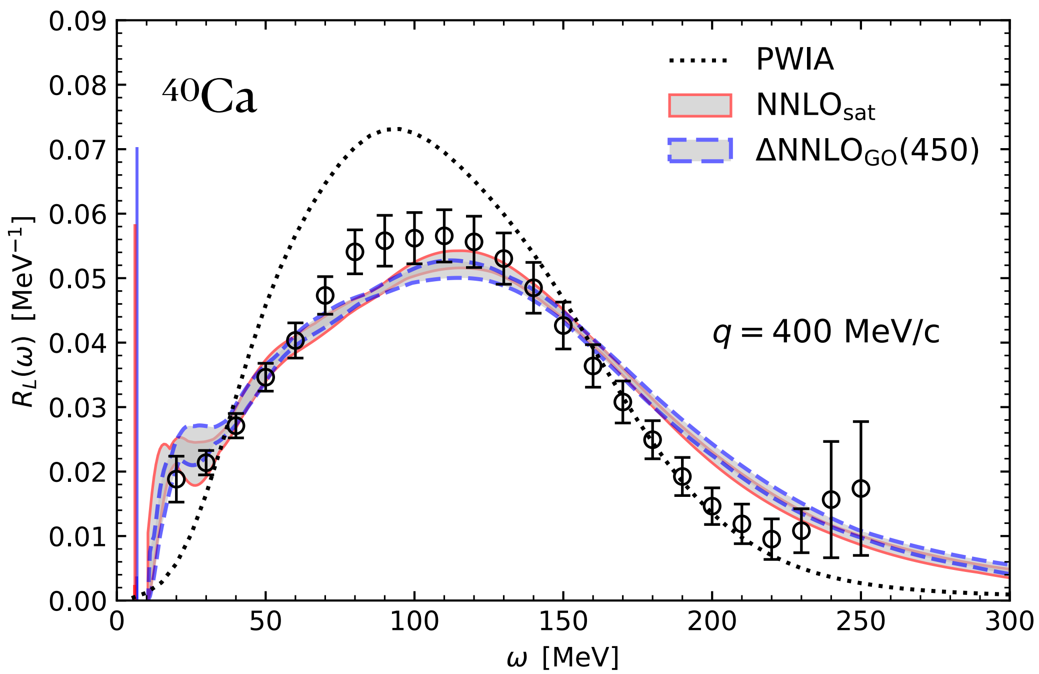
JES, B. Acharya, S. Bacca, G. Hagen; *PRL* 127 (2021) 7, 072501

Uncertainty band: inversion of LIT

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

Longitudinal response ^{40}Ca



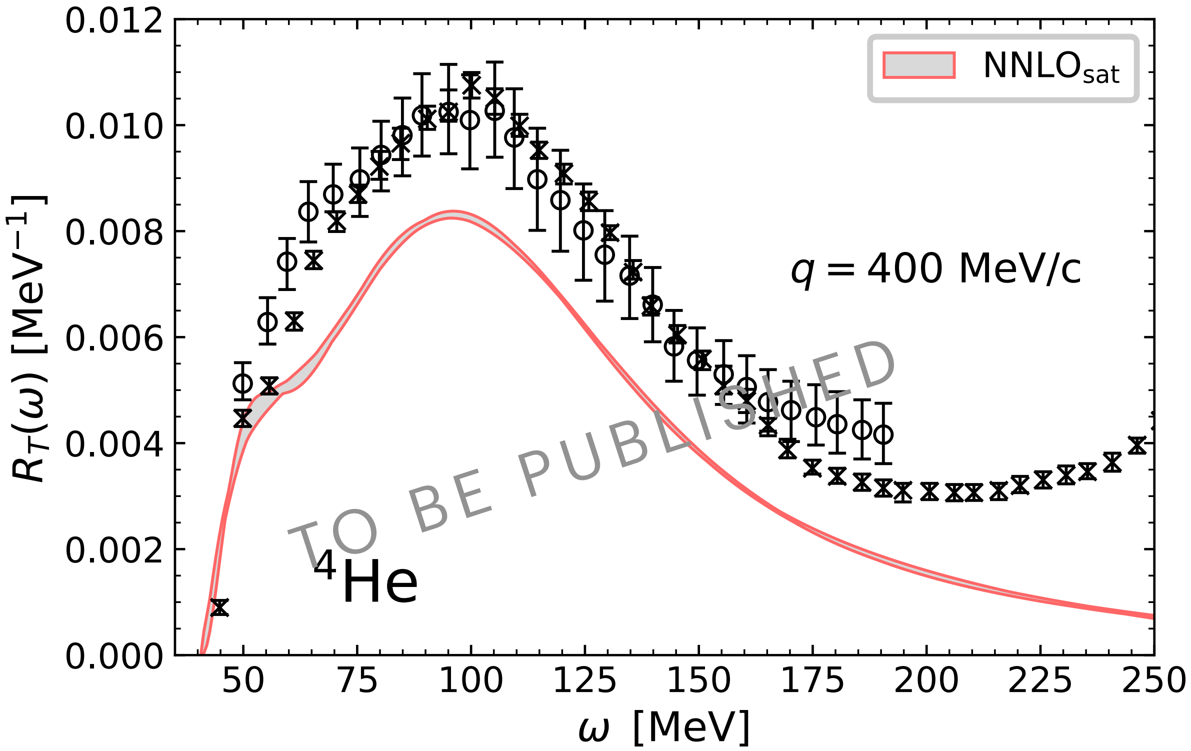


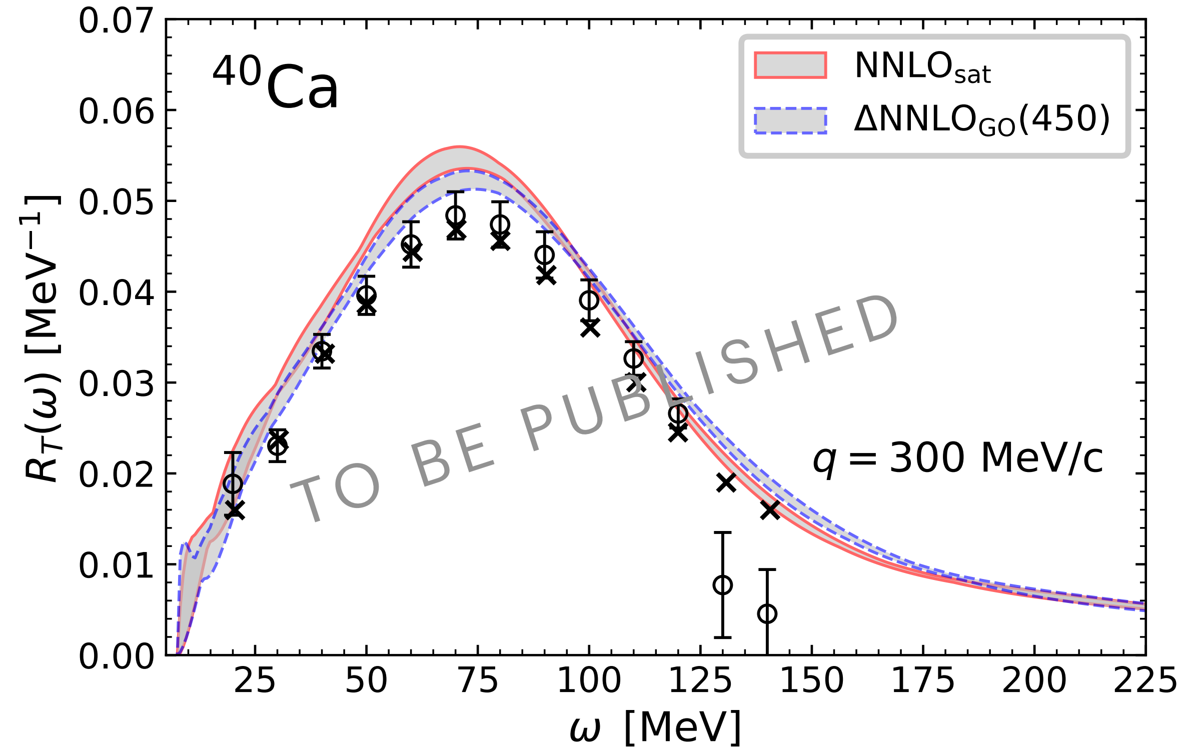
JES, B. Acharya, S. Bacca, G. Hagen; *PRL* 127 (2021) 7, 072501

- ✓ Coupled cluster singles & doubles
- ✓ Two different chiral Hamiltonians
- ✓ Uncertainty from LIT inversion

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

Transverse response





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

➡ This allows to predict electron-nucleus cross-section

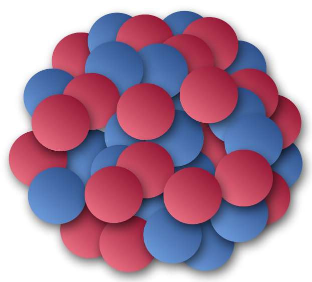
➡ Currently only 1-body current

2-body currents important for ^{4}He

→ more correlations needed?

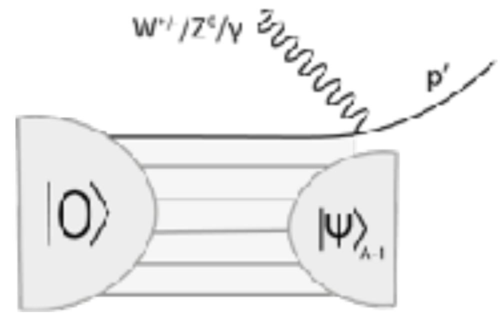
→ 2-body currents strength depends on nucleus?

Low/high energies

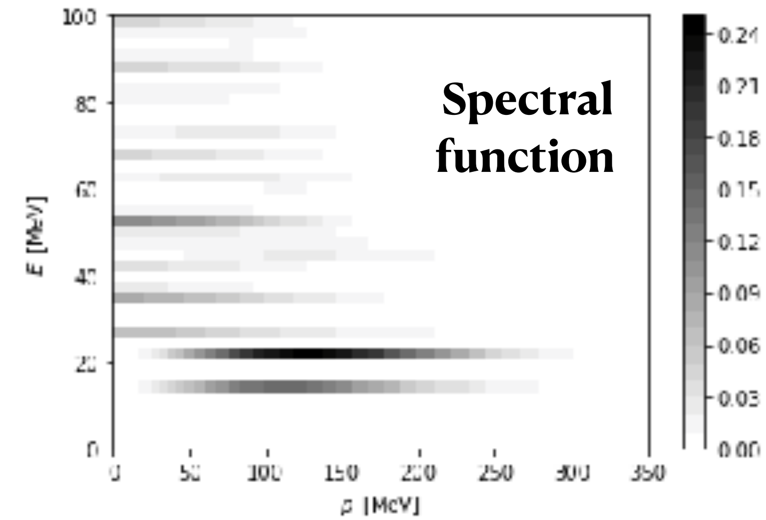


$$\hat{H}\,|\psi_A\rangle = E\,|\psi_A\rangle$$

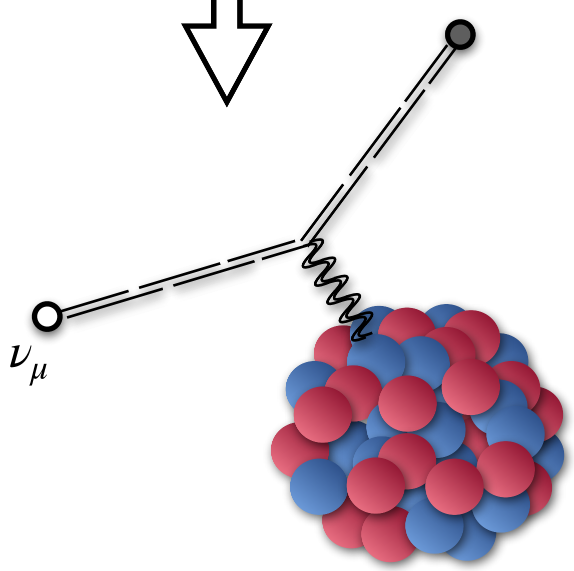
Many-body problem



Impulse Approximation

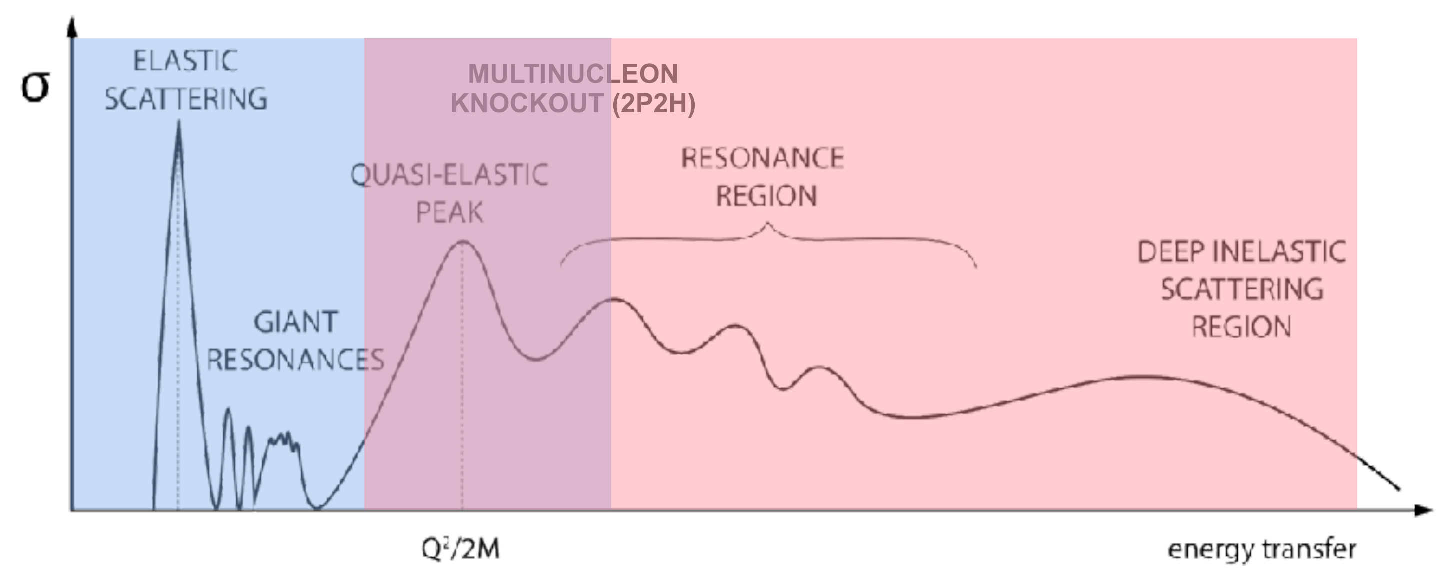


Probability density of finding nucleon $(E, \mathbf{p})$ in ground state nucleus



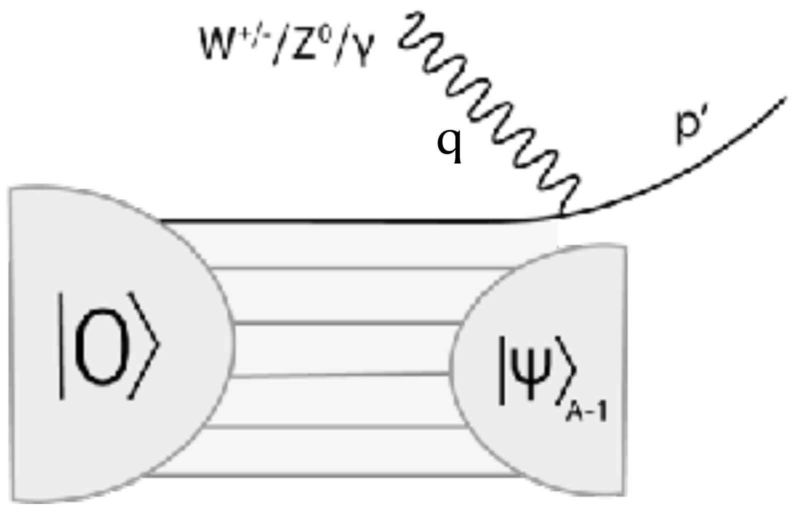
$$\langle \psi_f\,|\,\hat{j}\,|\,\psi_A\rangle$$

Electroweak responses



Spectral functions

from Coupled Cluster

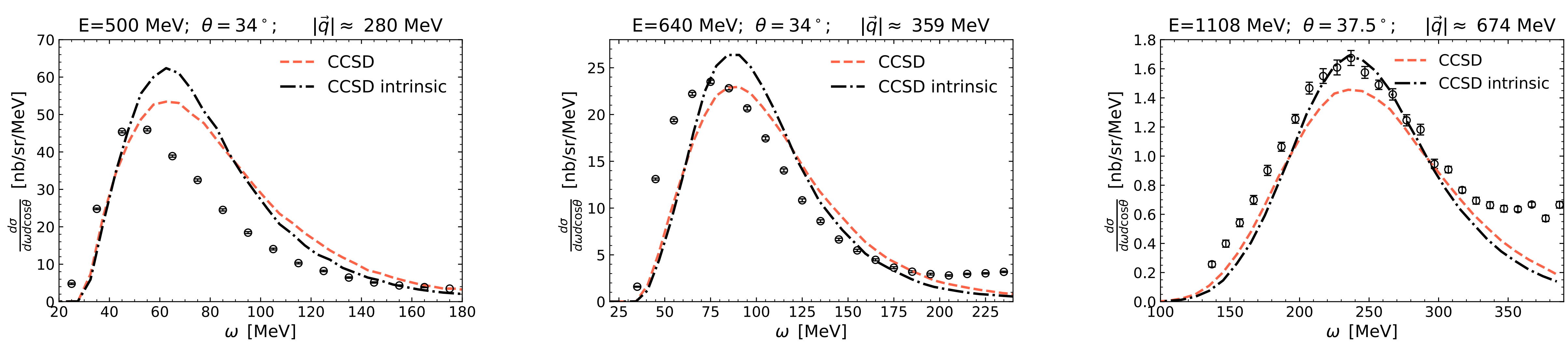


$$\sigma \propto |\mathscr{M}|^2 S(E,p)$$

Factorized interaction vertex (relativistic, pion production...)

Spectral function - nuclear information

growing **q** momentum transfer → final state interactions play minor role



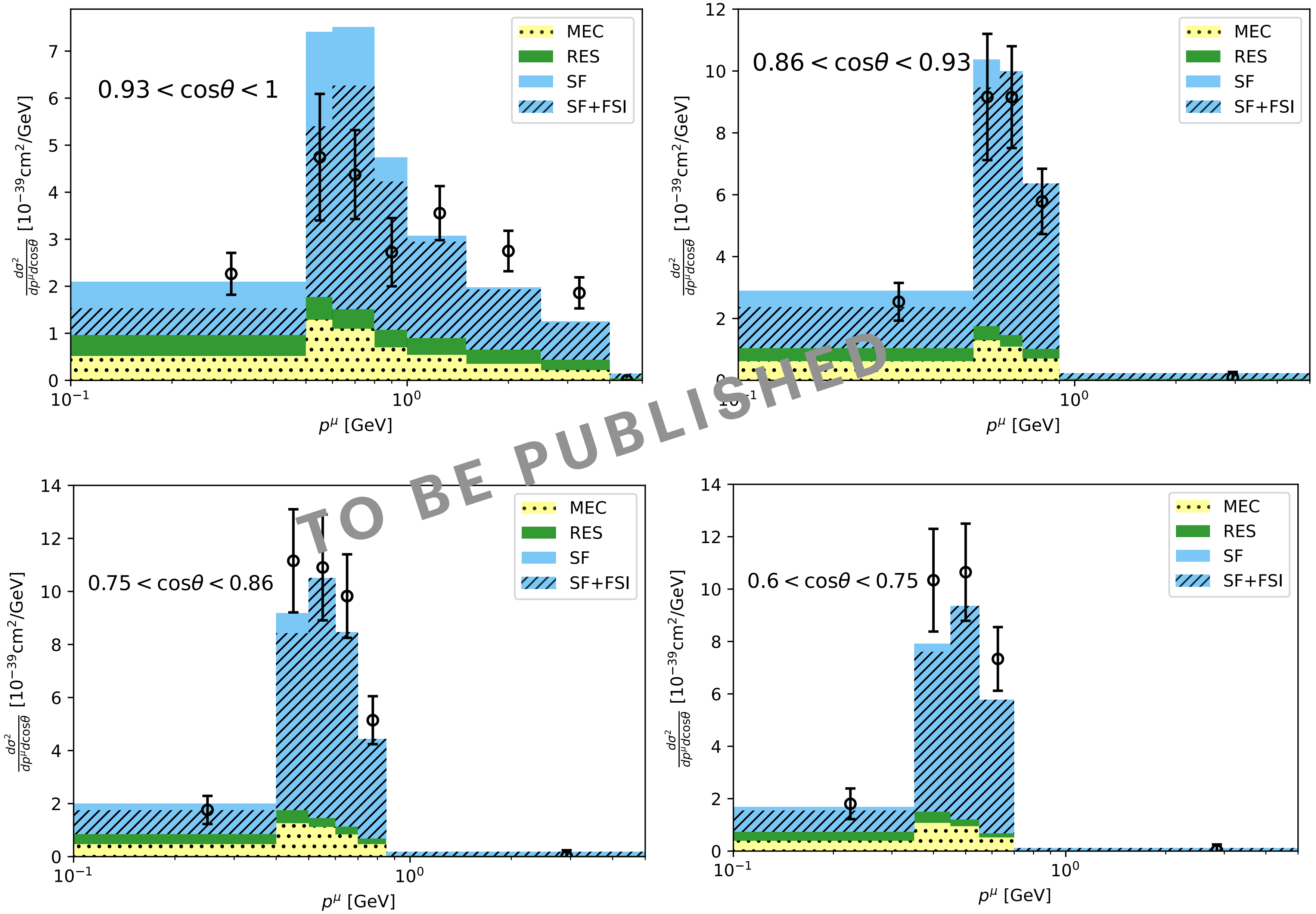
JES, S. Bacca, G. Hagen, T. Papenbrock *arXiv:* 2205.03592 accepted in Phys. Rev. C

Spectral function for neutrinos

$$\nu_\mu + {}^{16}\mathrm{O} \rightarrow \mu^- + X$$

- Comparison with T2K long baseline ν oscillation experiment
- CC0π events
- Spectral function implemented into NuWro Monte Carlo generator

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



JES et al, in preparation (2022)

Outlook

- First results from the coupled cluster theory: on the way to obtain cross-section for neutrino scattering on medium-mass nuclei
- Role of 2-body currents and FSI for medium-mass nuclei
- Spectral functions (within Impulse Approximation):
    - Relativistic regime
    - Semi-inclusive processes
    - Further steps: 2-body spectral functions, accounting for FSI

Thank you for attention

BACKUP

Lorentz Integral Transform (LIT)

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

continuum spectrum

Integral transform

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

Lorentzian kernel:

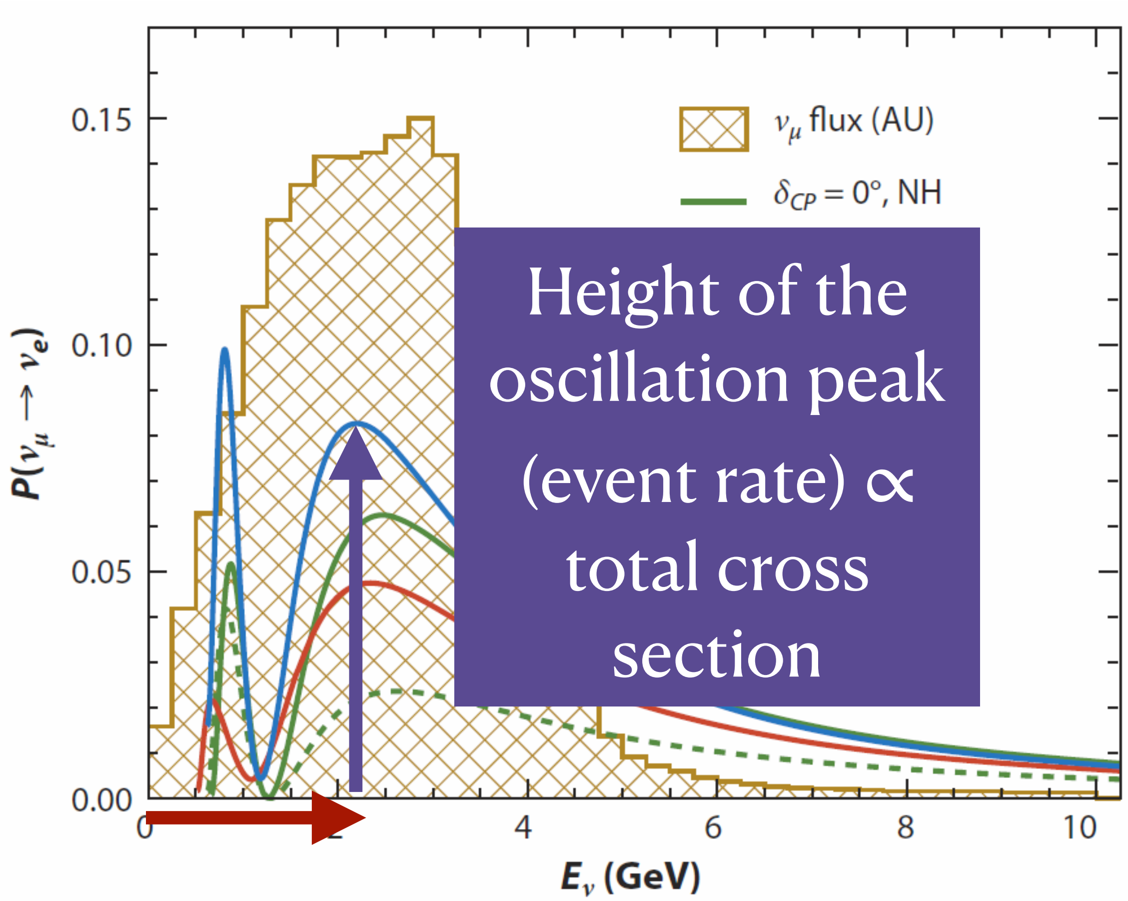
$$K_\Gamma(\omega, \sigma) = \frac{1}{\pi} \frac{\Gamma}{\Gamma^2 + (\omega - \sigma)^2}$$

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

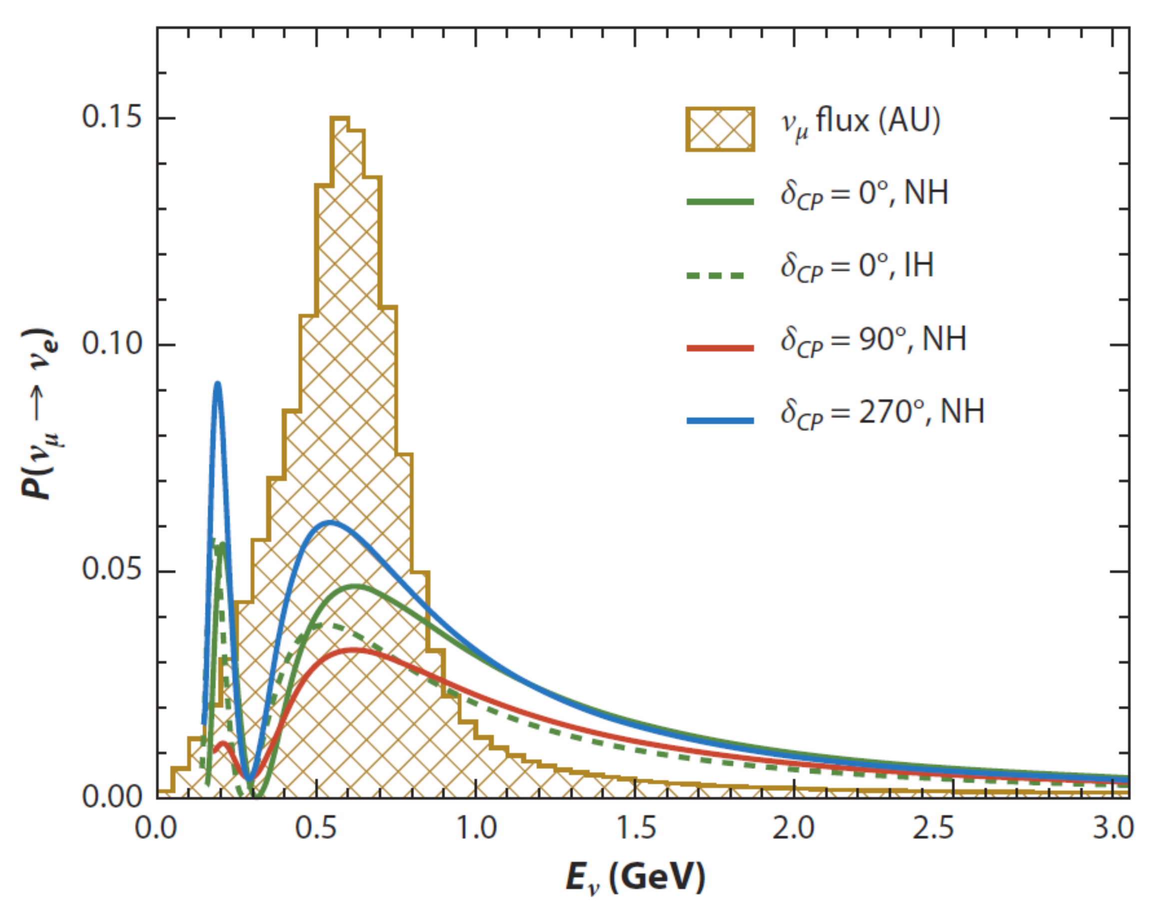
Aims & challenges

From: Diwan et al, Ann.Rev.Nucl. Part. Sci 66 (2016)

DUNE



T2HK

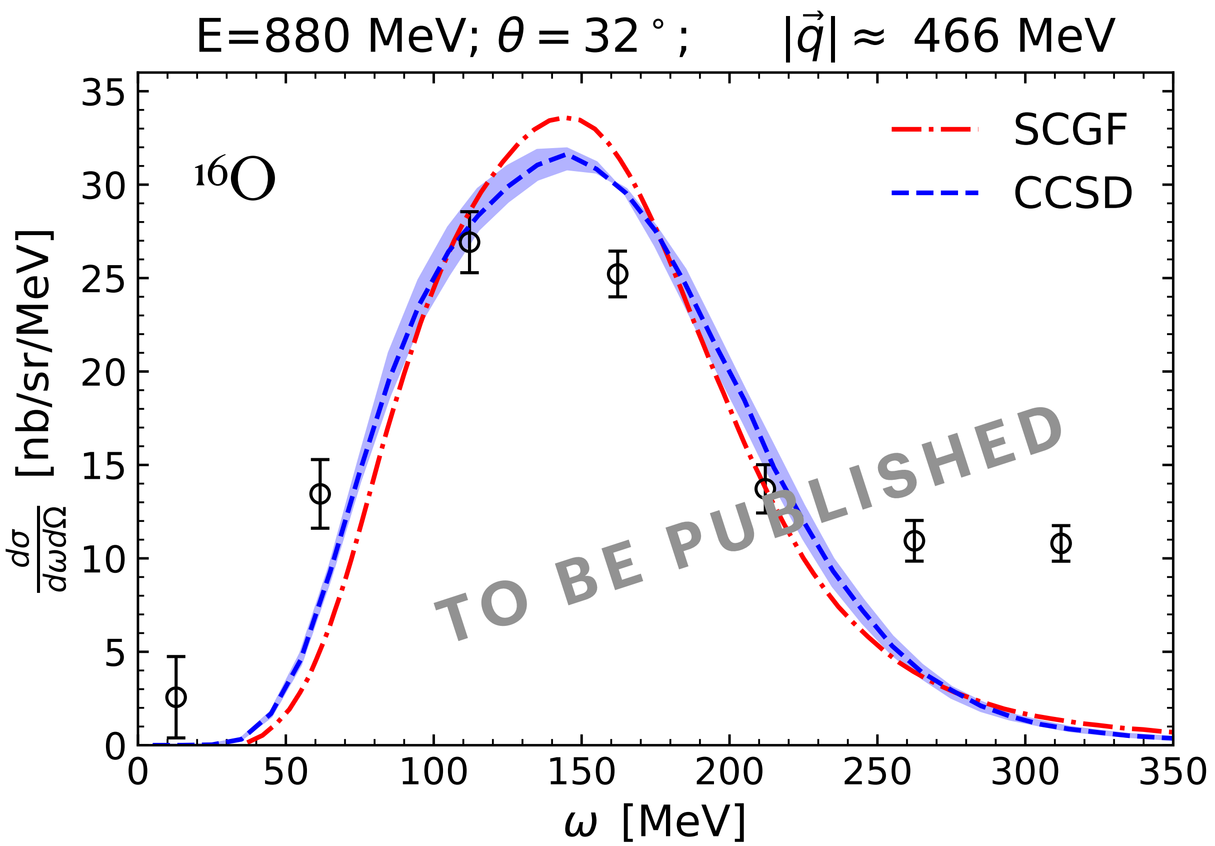


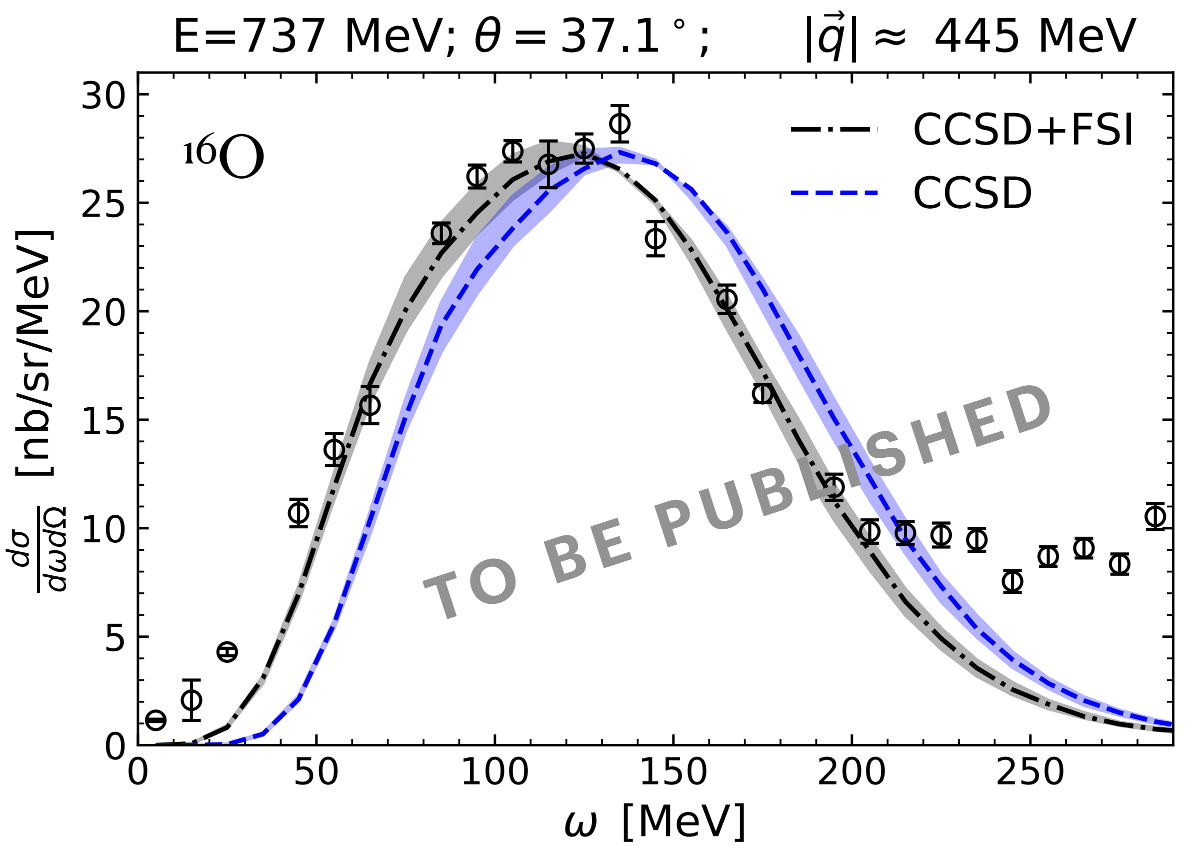
Position of the oscillation peak depends on energy reconstruction

DUNE aims at uncertainties < 1% meaning O(25 MeV) precision of energy reconstruction

Systematic errors should be small since statistics will be high.

Final state interactions





JES et al, in preparation (2022)

How to account for the FSI? Optical potential for the outgoing nucleon