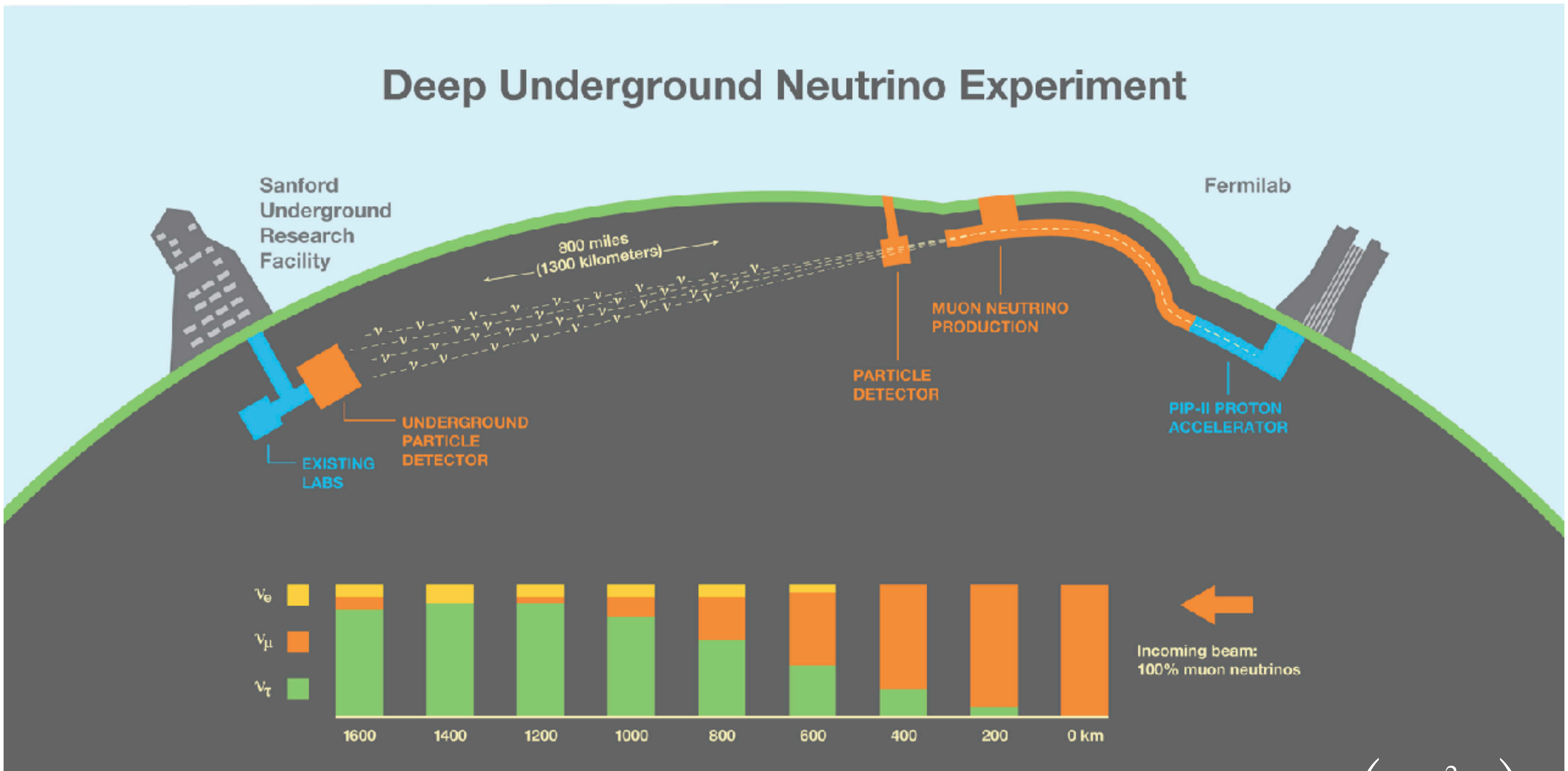
Electroweak responses in nuclear systems

Joanna Sobczyk

Hirschegg, 20 January 2026

CHALMERS
UNIVERSITY OF TECHNOLOGY

Motivation: neutrino oscillations

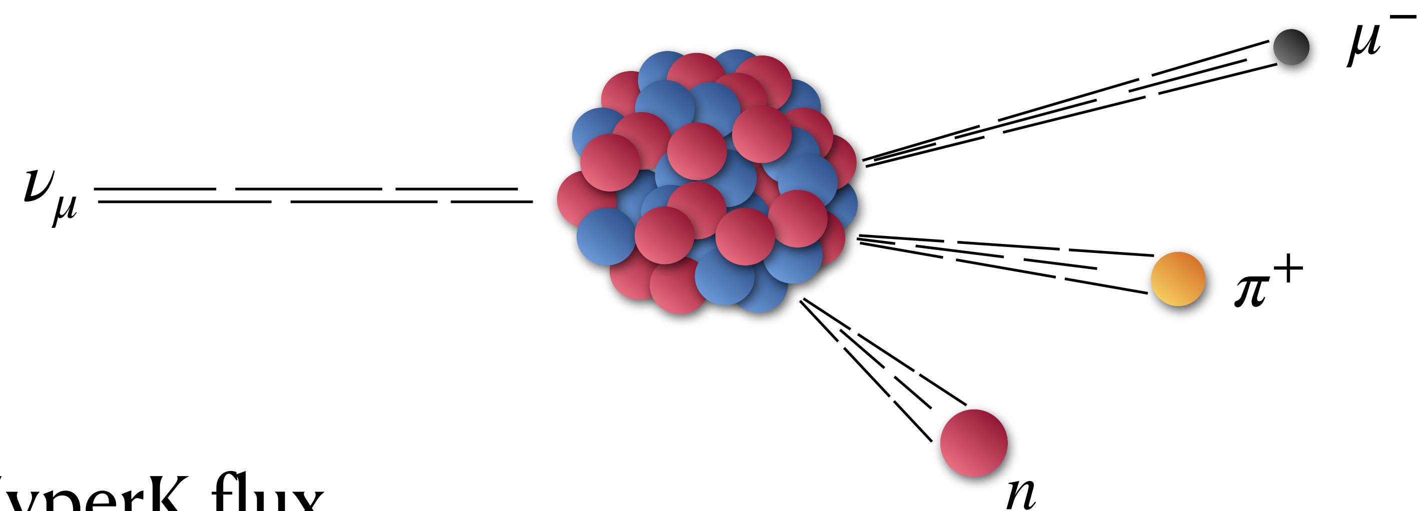


$$\mathscr{P}_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)$$

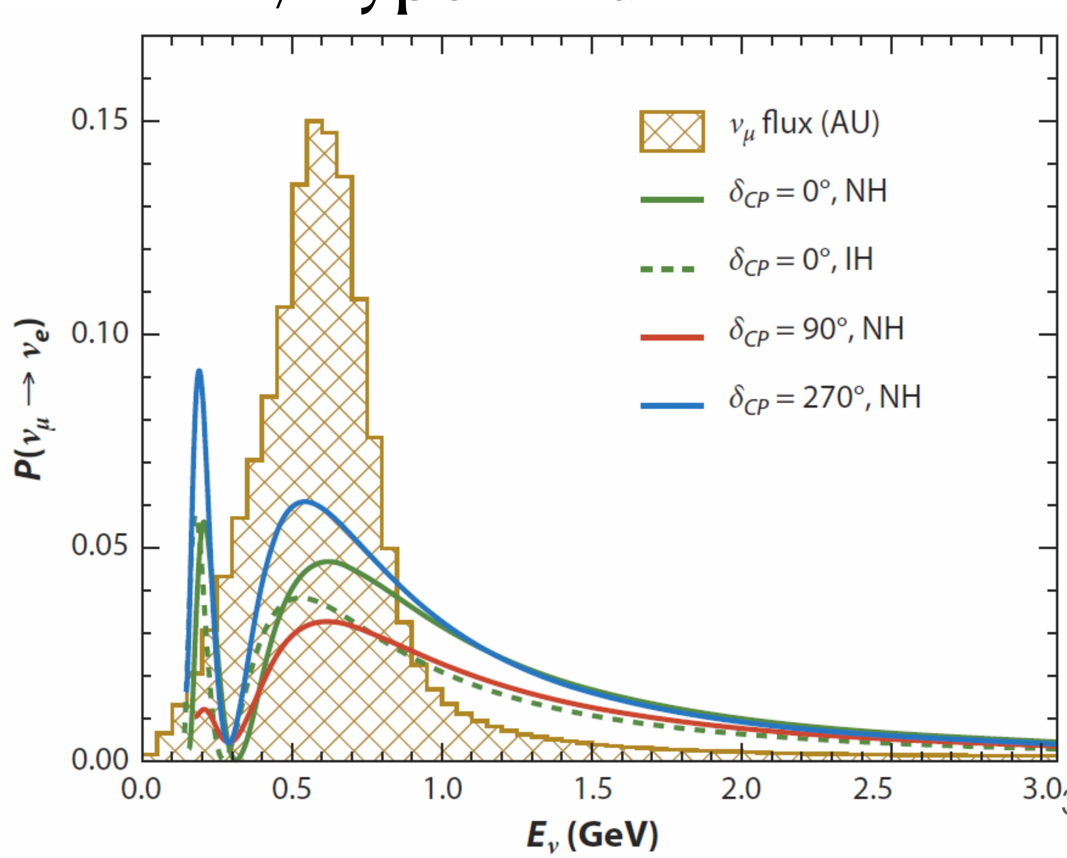
source: www.dunescience.org

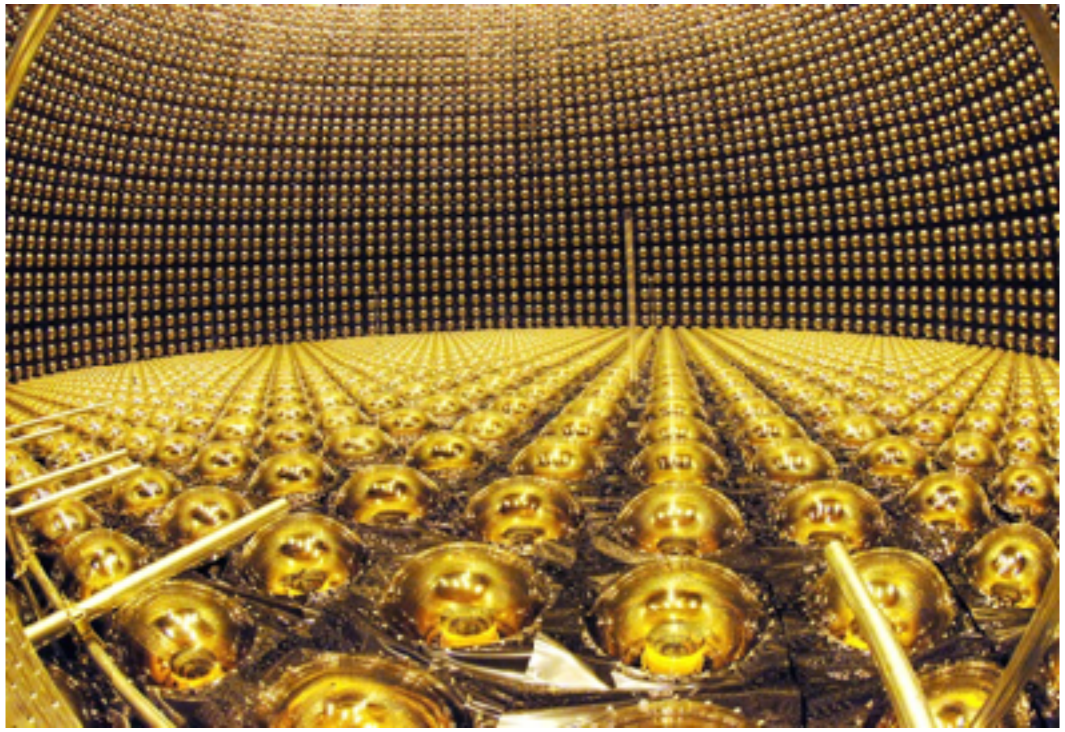
Motivation:
long-baseline oscillation experiments

$E_\nu = ?$



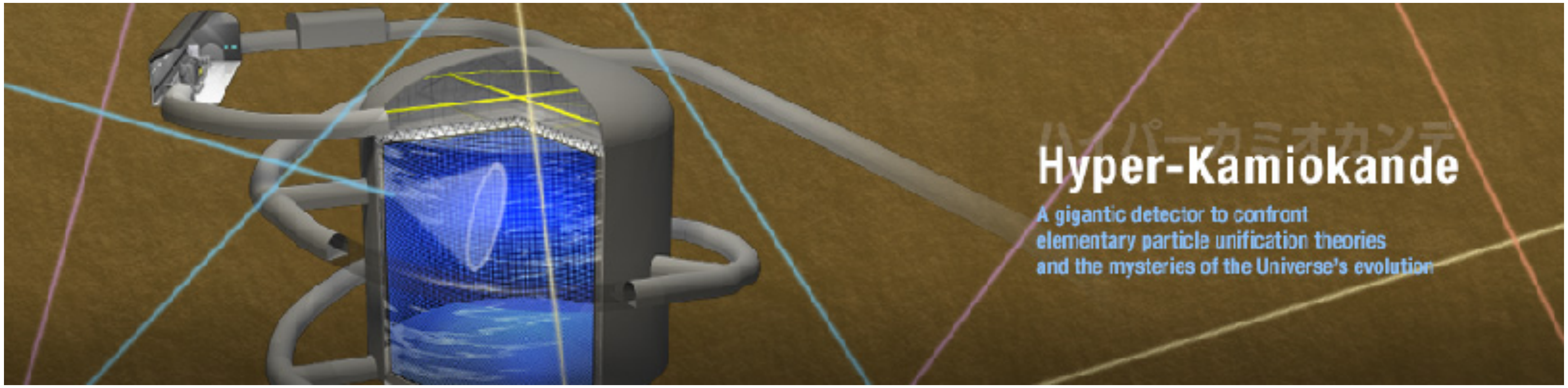
T2K/HyperK flux

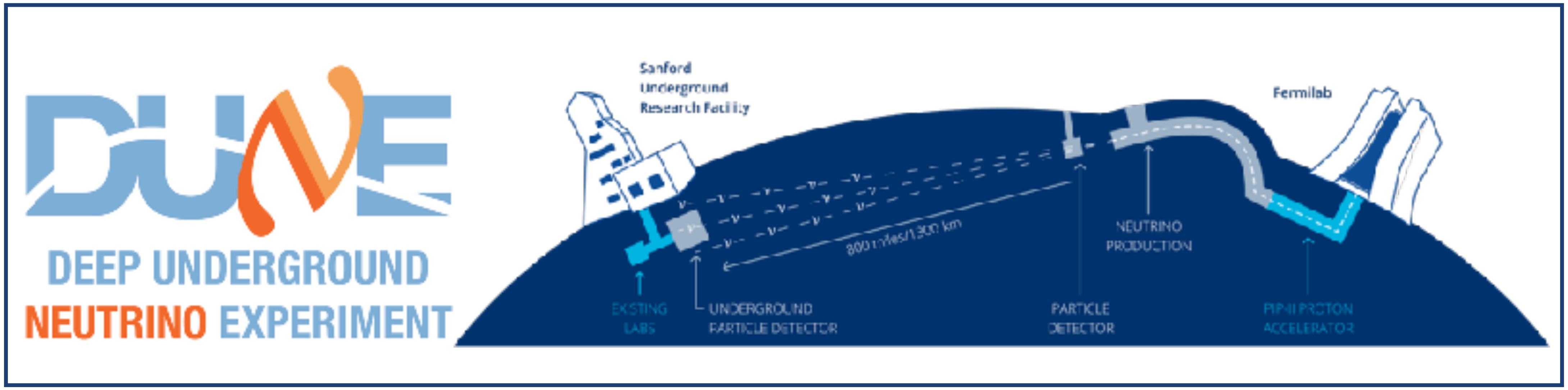




Next generation experiments

Long-baseline oscillation experiments

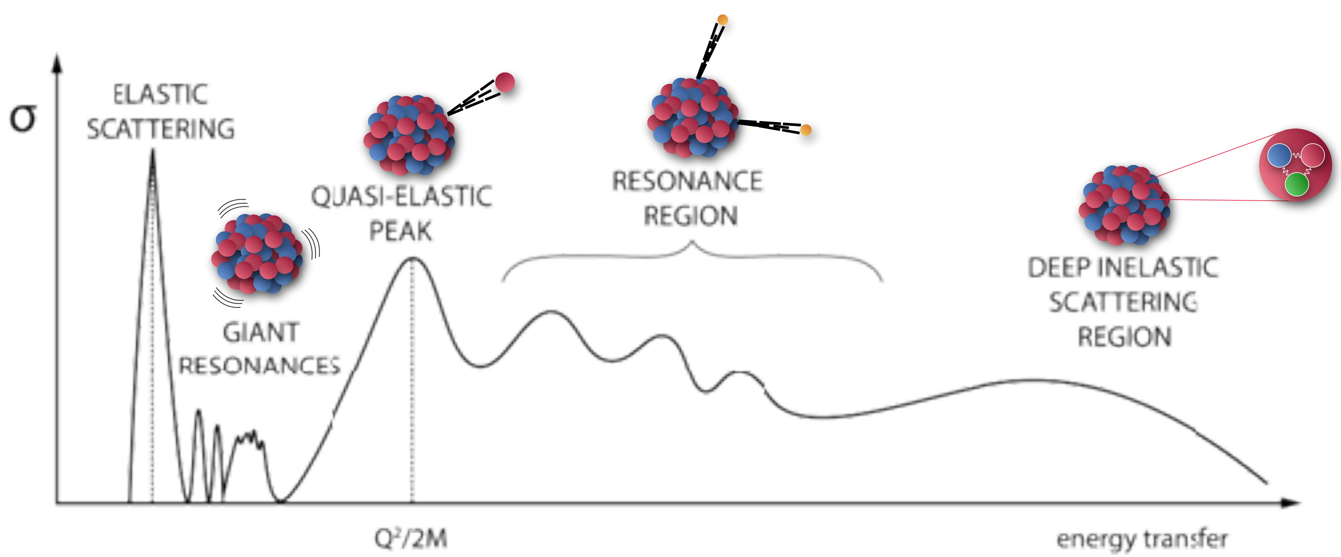




- ✓ **CP-violation measurement**
- ✓ **Determining ν mass ordering**
- ✓ Proton decay searches
- ✓ Cosmic neutrino observation

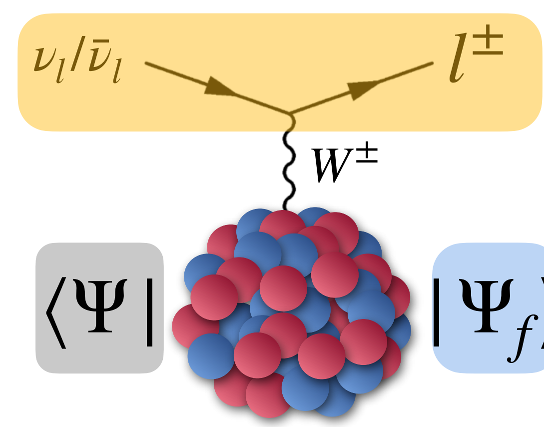
Nuclear responses

Cross-section $\sigma \propto L^{\mu\nu} R_{\mu\nu}$



lepton tensor

nuclear responses



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

Challenging sum over continuum spectrum

Electrons for neutrinos

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

$$\left.\frac{d\sigma}{dE'd\Omega}\right|_{e} = \sigma_M\Big(v_L R_L(\omega,\bar{q}) + v_T R_T(\omega,\bar{q})\Big)$$

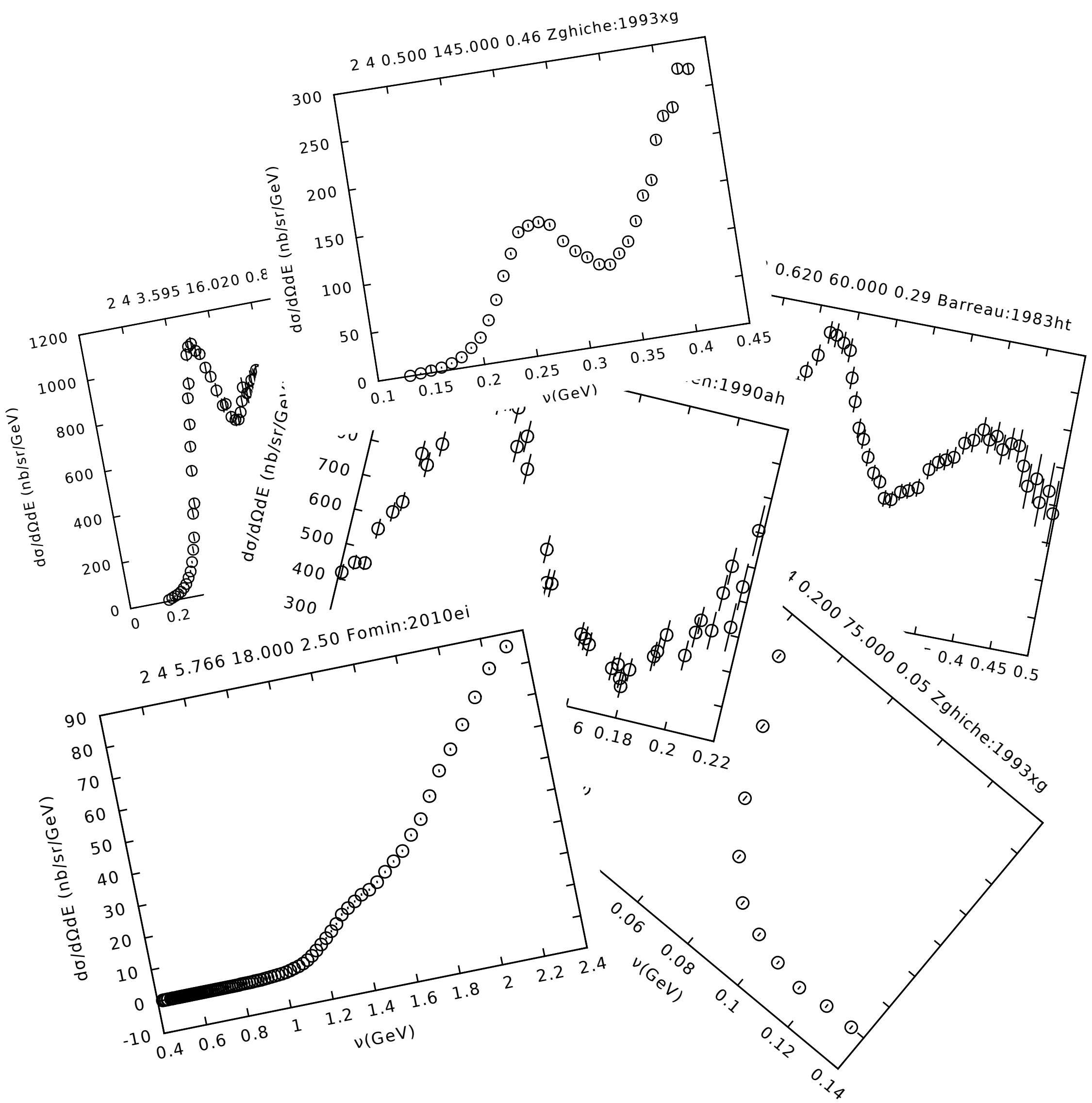
✓ much more precise data

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

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

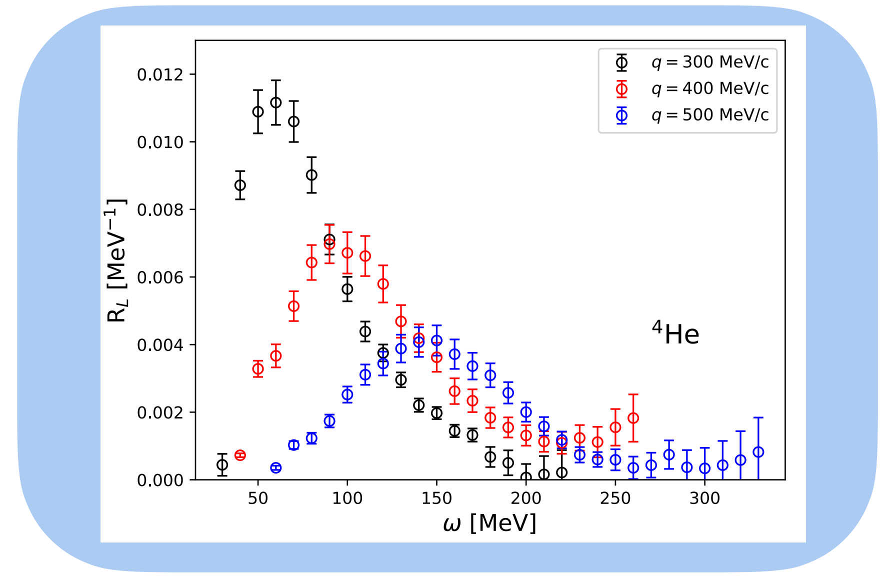
Electron scattering: Rosenbluth separation

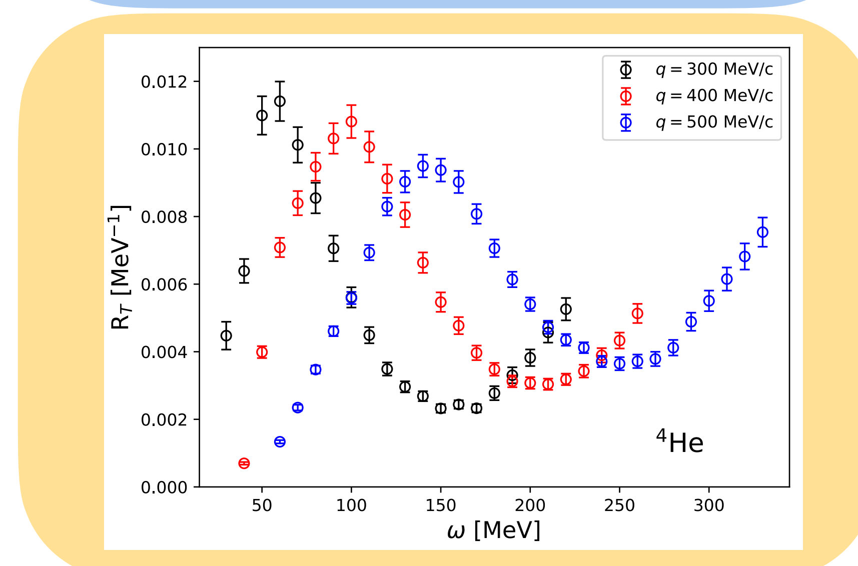
Inclusive cross-section



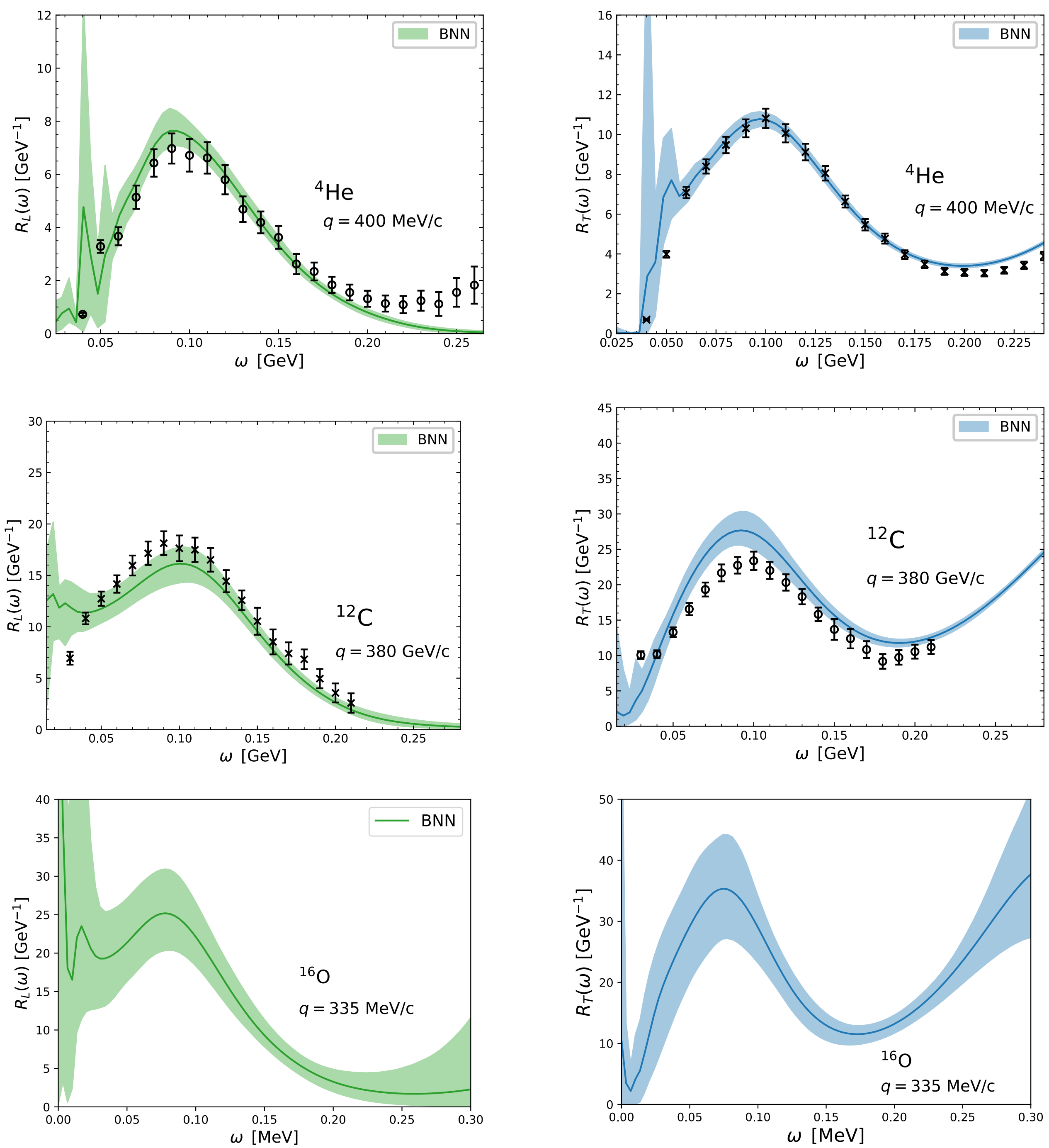
$$\left.\frac{d\sigma}{dE'd\Omega}\right|_e$$

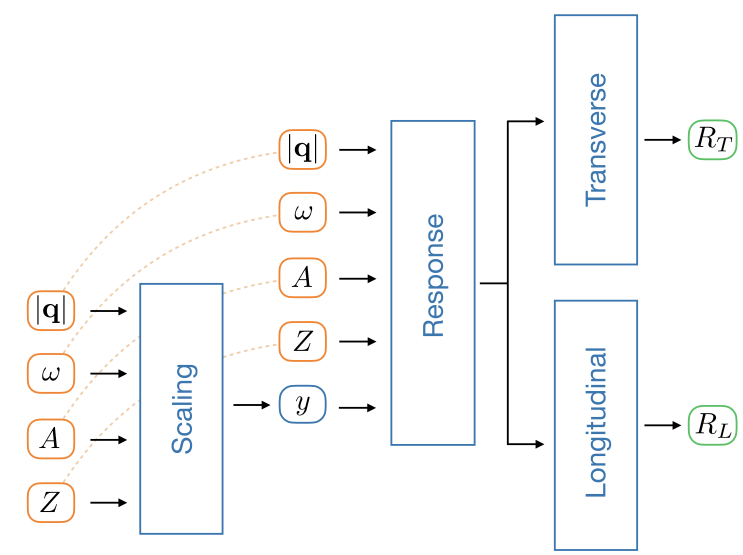
Nuclear responses





Rosenbluth separation with Bayesian neural network





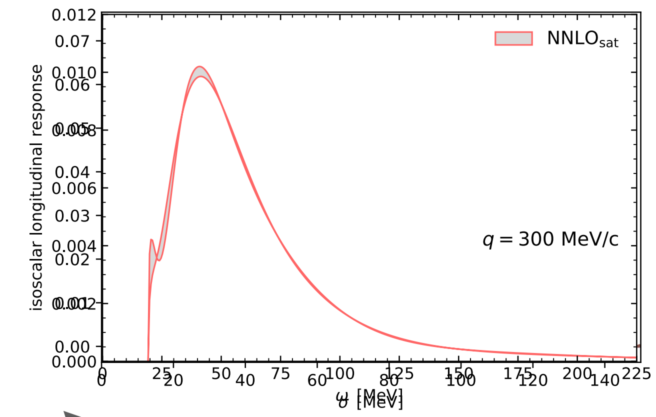
- Trained on ^{4}He, ^{6}Li, ^{12}C, ^{16}O, ^{40}Ca
- Rosenbluth separation possible for kinematics and nuclei where there is less data

JES, N.Rocco, A.Lovato, Phys. Lett. B 859 (2024) 139142

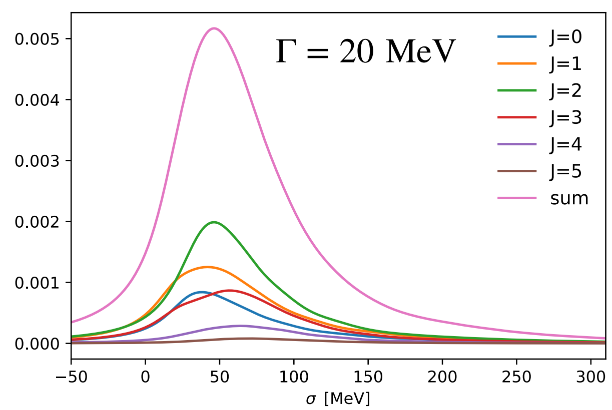
Lorentz Integral Transform (LIT)

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

continuum spectrum



Integral transform



Inversion of $S_{\mu\nu}$

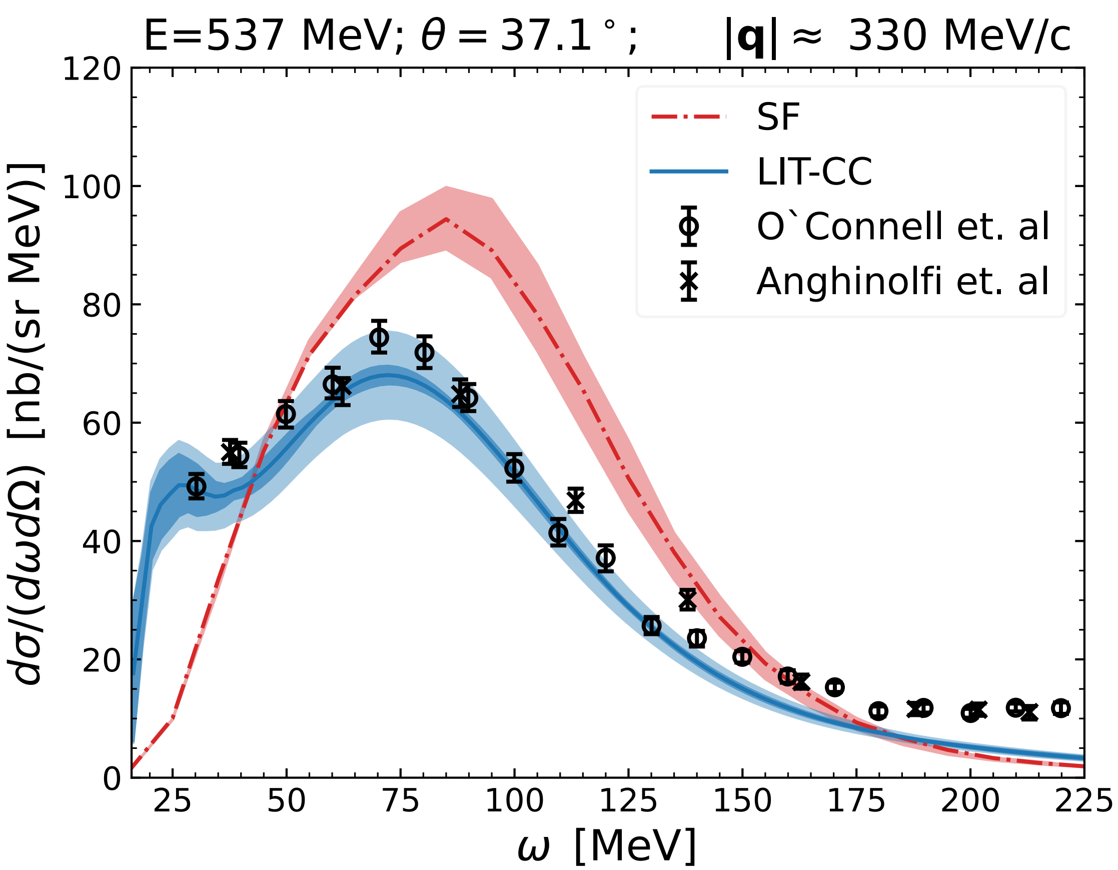
$$S_{\mu\nu}(\sigma, q) = \int d\omega K(\omega, \sigma) R_{\mu\nu}(\omega, q) = \langle \Psi | J_\mu^\dagger \, K(\mathscr{H} - E_0, \sigma) \, J_\nu | \Psi \rangle$$

Lorentzian kernel:

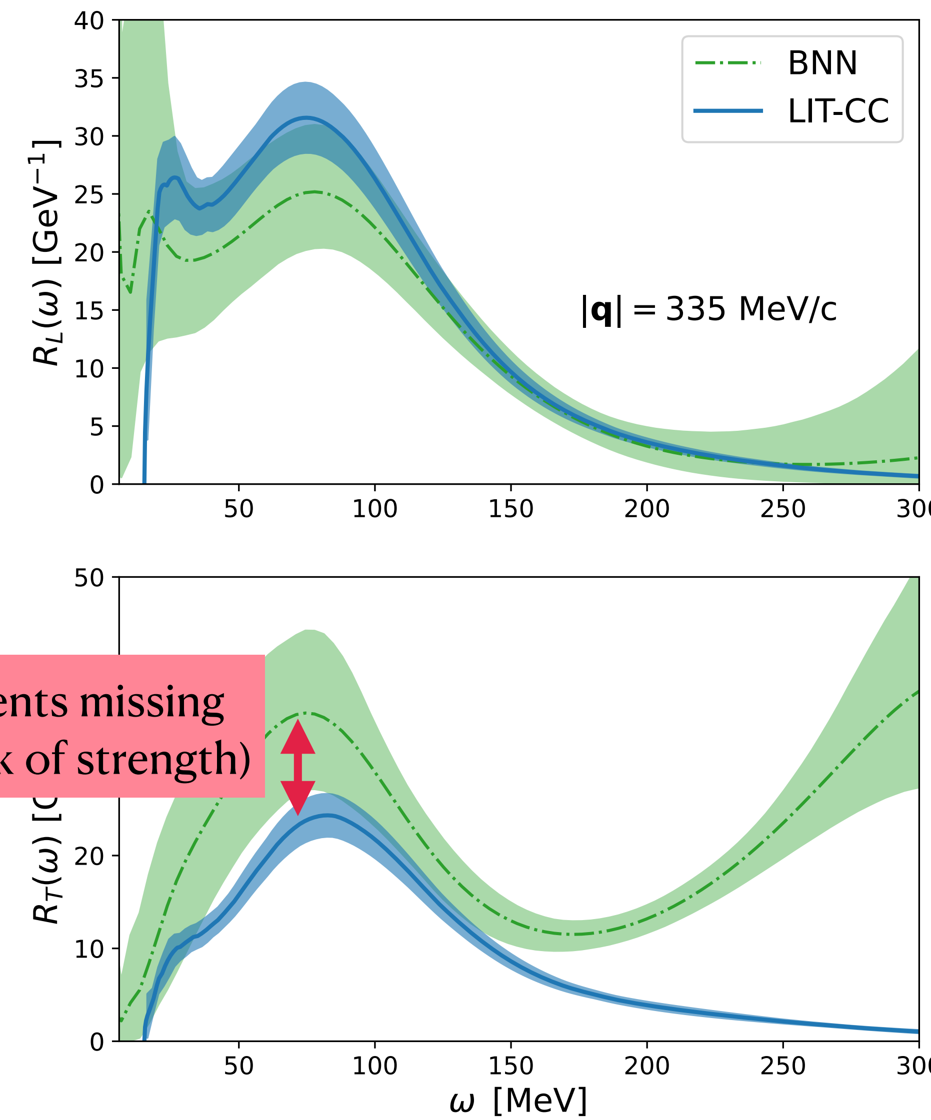
$$K_\Lambda(\omega, \sigma) = \frac{1}{\pi} \frac{\Lambda}{\Lambda^2 + (\omega - \sigma)^2}$$

Electron scattering on ^{16}O

Lorentz Integral Transform + Coupled Cluster **(LIT-CC)**



First ab-initio result for many-body system of 16 nucleons



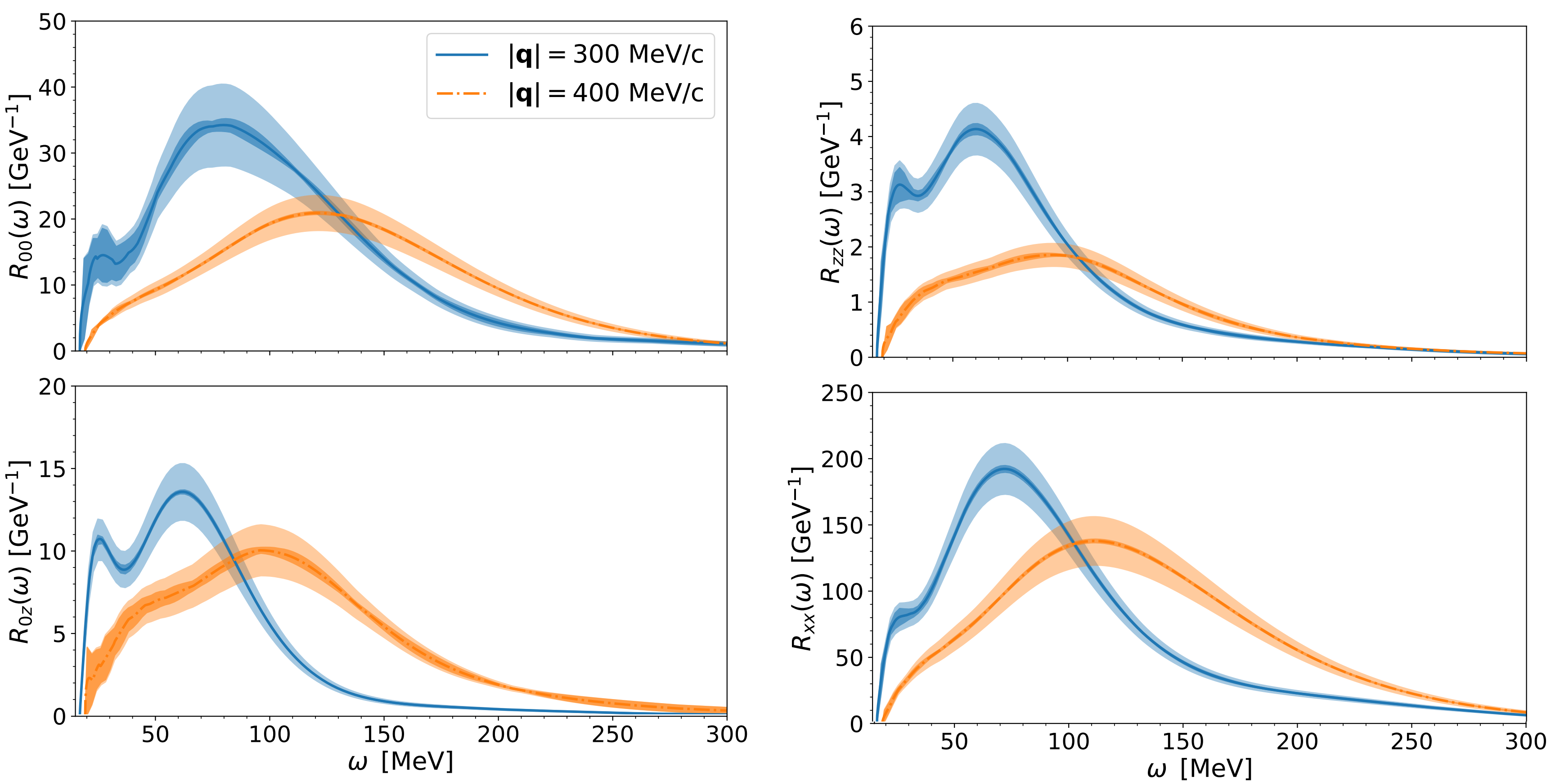
2-body currents missing (expected lack of strength)

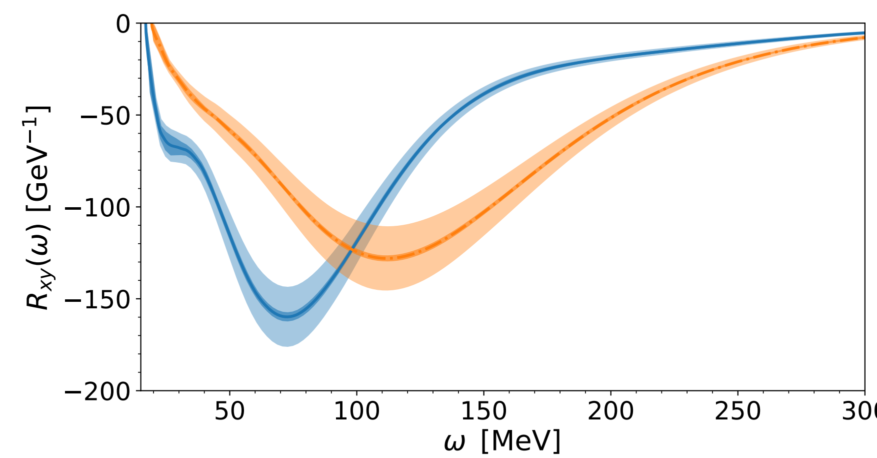
B.Acharya, JES, S. Bacca, G. Hagen W. Jiang, *Phys. Rev. Lett. 134.202501 (2025)*

Neutrino scattering on ^{16}O

LIT-CC

$$\left.\frac{d\sigma}{dE'd\Omega}\right|_{\nu/\bar{\nu}} = \sigma_0\left(v_{00}R_{00} + v_{0z}R_{0z} + v_{zz}R_{zz} + v_T R_T \pm v_{xy}R_{xy}\right)$$





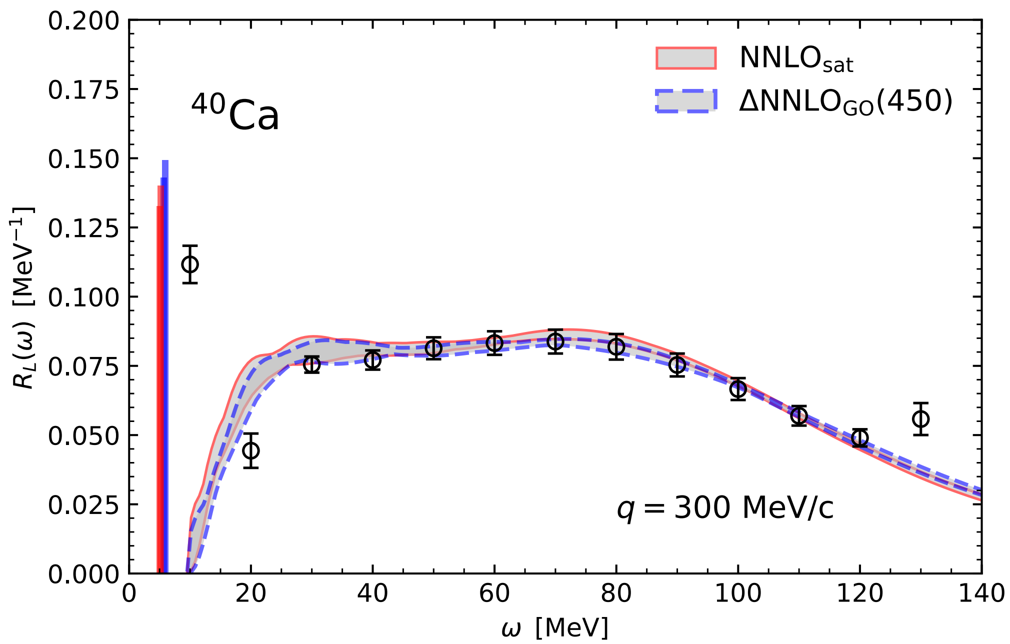
Uncertainty band:
truncation in chiral expansion of Hamiltonian
+ inversion procedure

NNLO$_{\text{sat}}$ as reference
ΔNLO$_{\text{GO}}$(450) + ΔNNLO$_{\text{GO}}$(450)
to estimate truncation

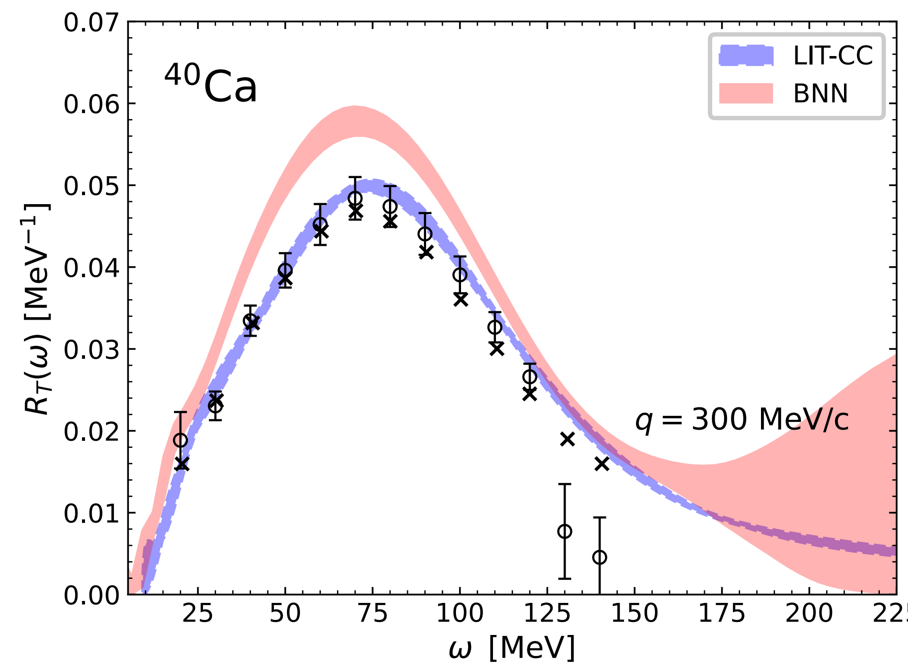
B.Acharya, JES, S. Bacca, G. Hagen W. Jiang,
Phys. Rev. Lett. 134.202501 (2025)

Electromagnetic responses on ^{40}Ca

(LIT-CC)



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



JES, B. Acharya, S. Bacca, G. Hagen;
Phys. Rev. C **109 (2024) 2, 025502**

✓ Coupled cluster singles & doubles

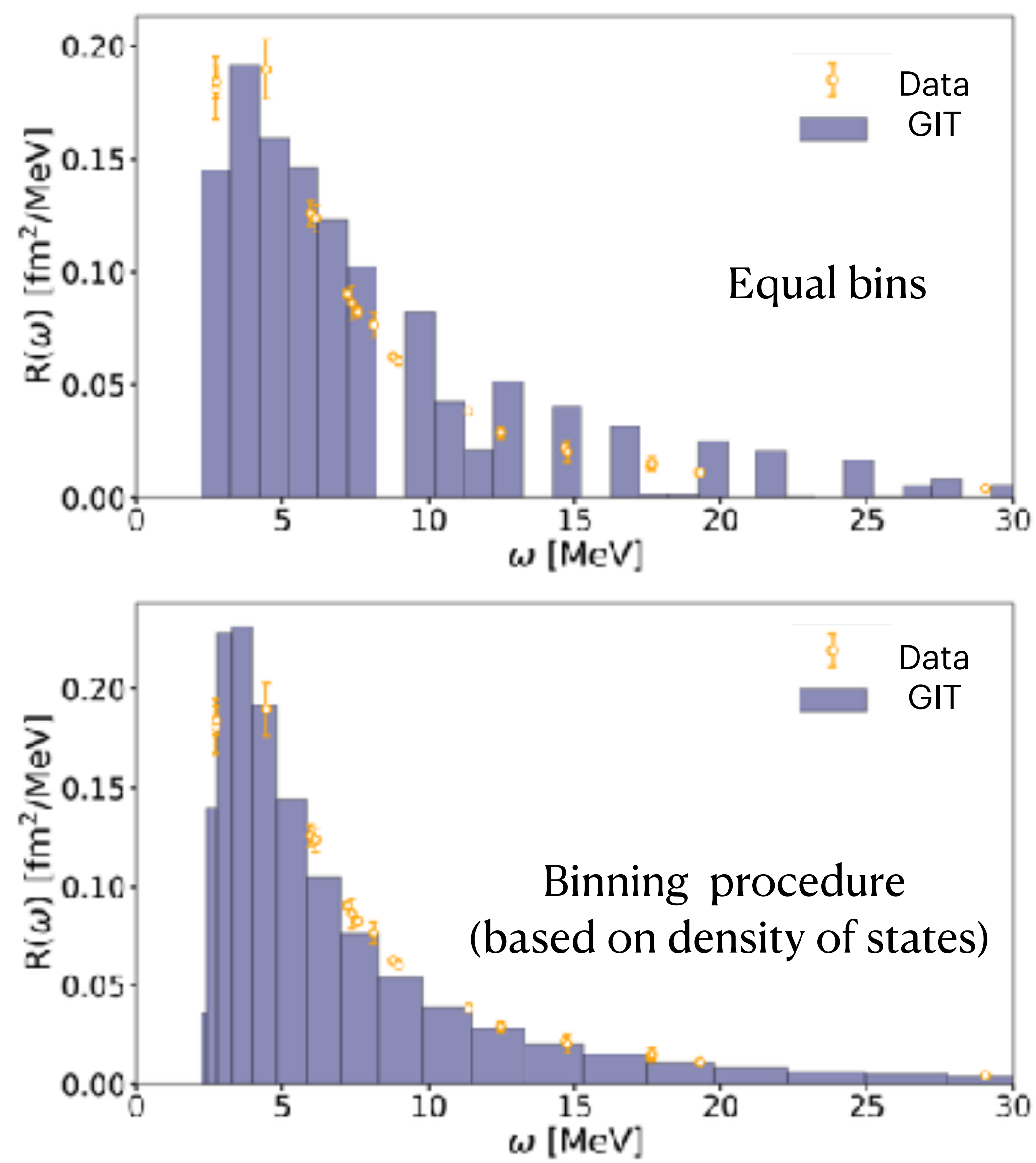
✓ Two different chiral Hamiltonians

✓ Uncertainty from LIT inversion

Alternative way to reconstruct response

- Inversion of LIT is an ill-posed problem + might be unstable.
- Alternative: reconstruct discretised spectrum in terms of histograms.
- Gaussian integral transform (GIT) reconstructed via Chebyshev polynomials
- Binning based on the density of states.
- Study on deuteron

Dipole response on deuteron



I. Reis, JES, S. Bacca, *Phys.Rev.C* 112 (2025) 4, 4

Alternative way to reconstruct response

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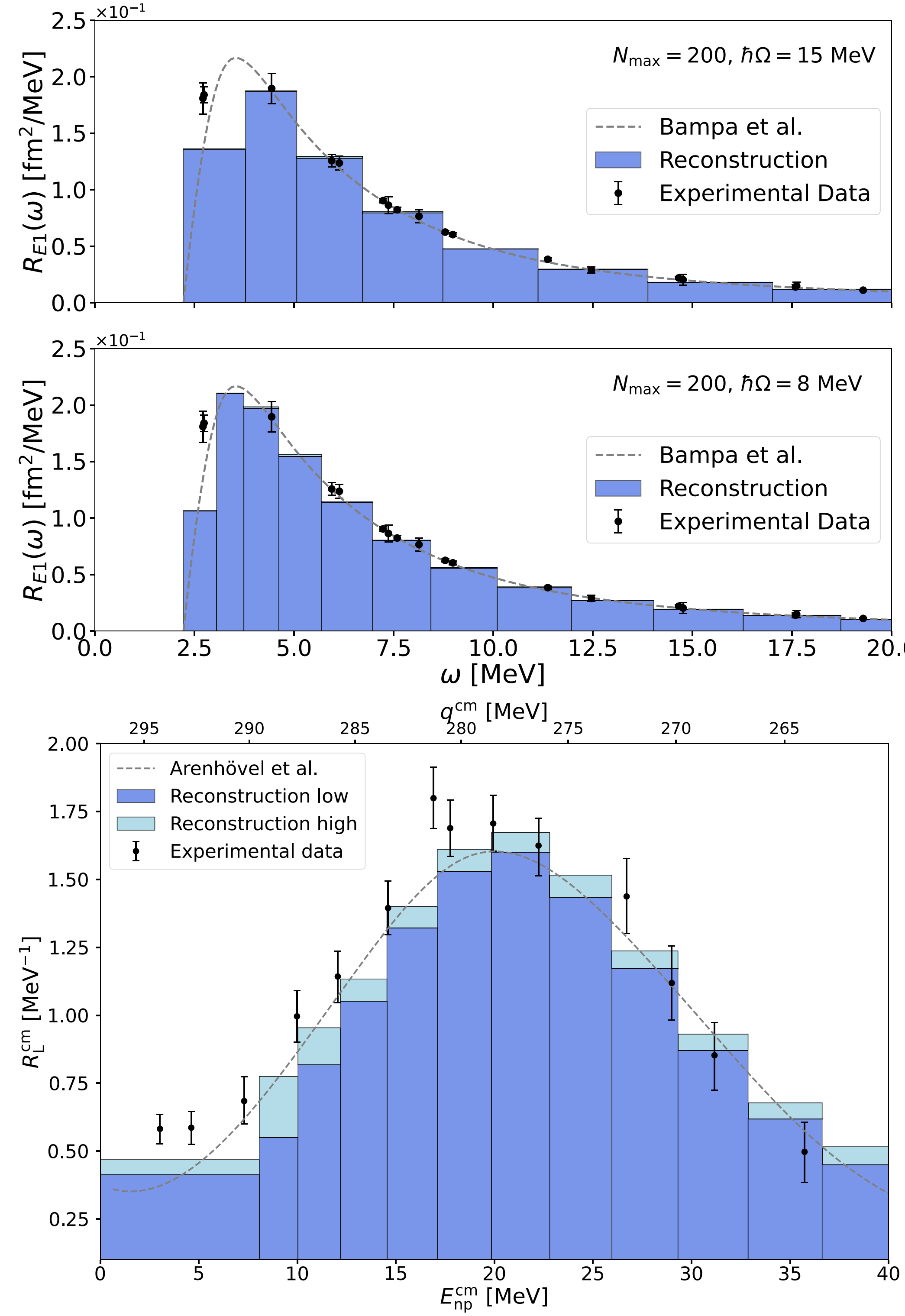
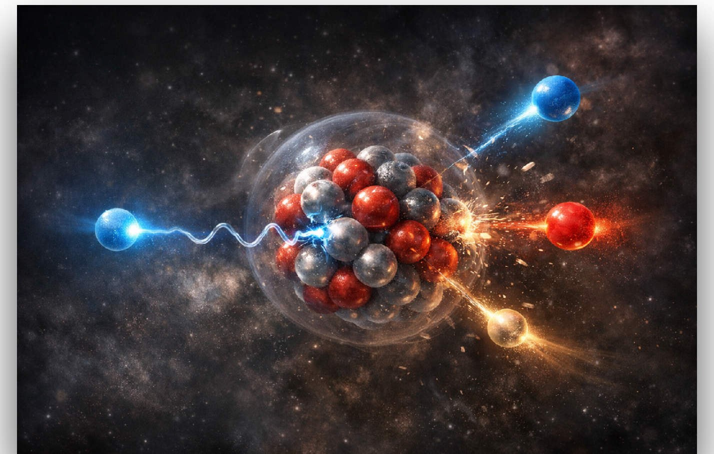


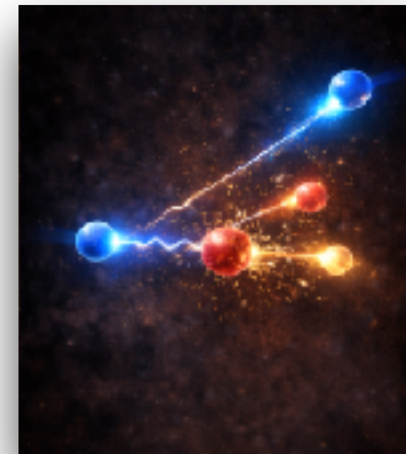
I. Reis, JES, S. Bacca, *Phys.Rev.C* 112 (2025) 4, 4

Towards semi-exclusive cross-sections

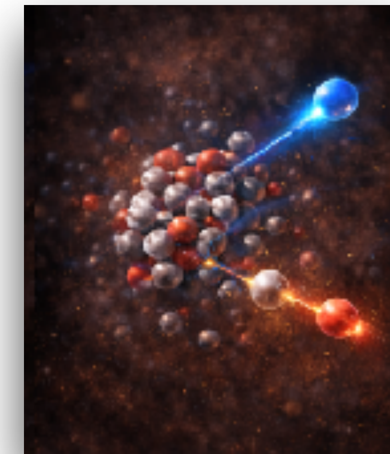


=

x



x

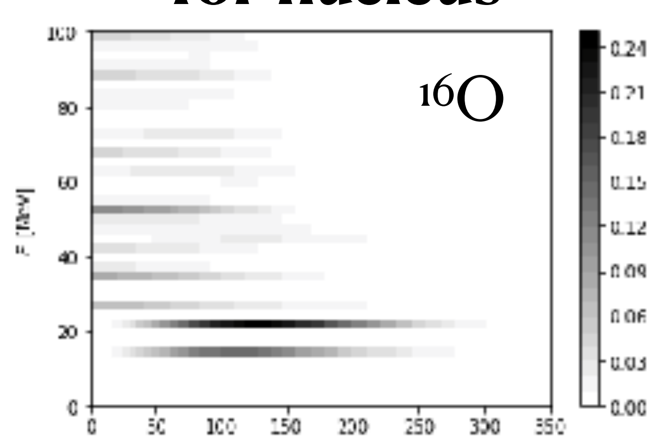


Initial nuclear state

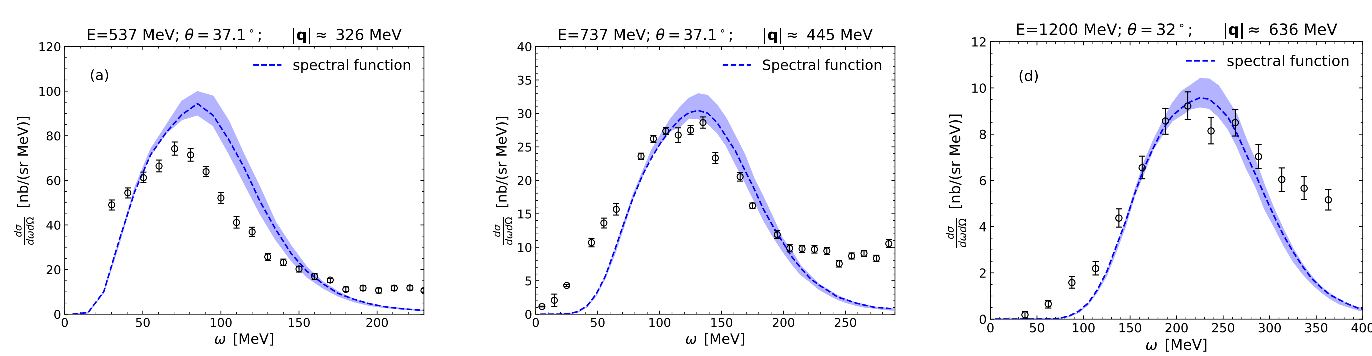
Vertex of interaction

Final state interactions

Spectral function for nucleus

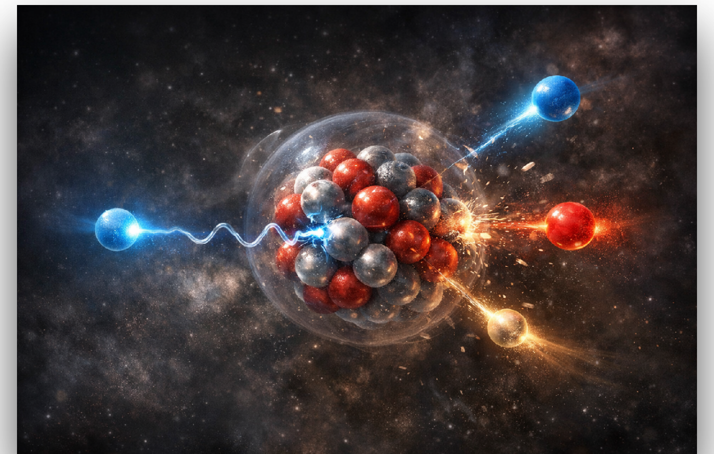


$$\sigma \propto |\mathcal{M}|^2 S(E,p)$$



JES , S. Bacca, ***Phys. Rev. C*** 109 044314

Towards semi-exclusive cross-sections



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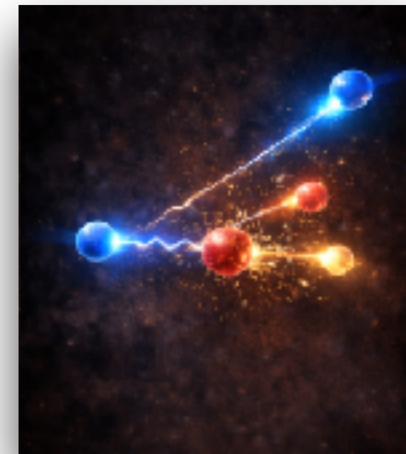
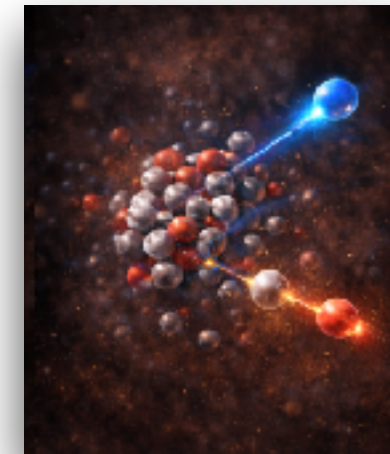
Initial nuclear state

x



Vertex of interaction

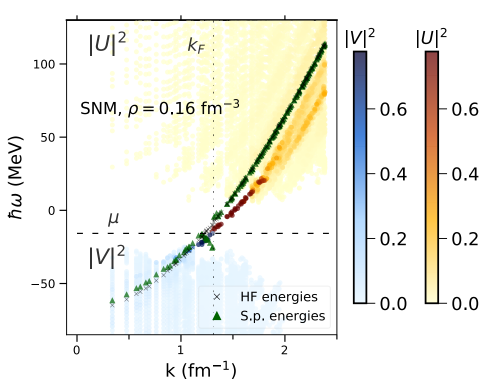
x

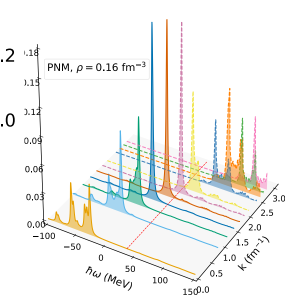


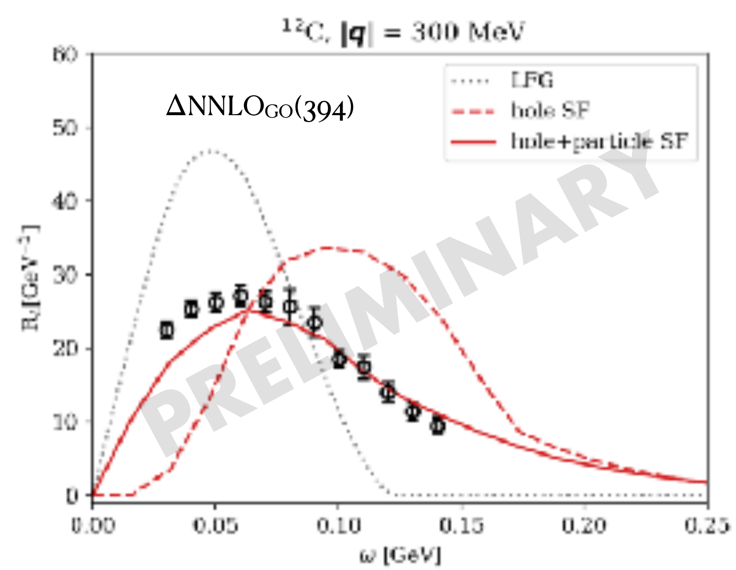
Final state interactions

Spectral function for nuclear matter

+Local density approximation





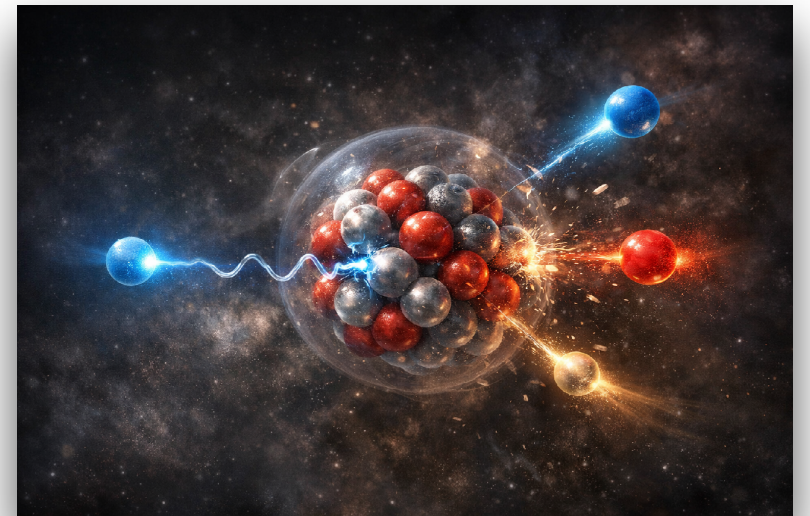


- Use NN to interpolate SF
- To be applied for symmetric nuclei
- For low momenta can use particle SF
- Can be interfaced with intra-nuclear cascade

F. Marino, C. Barbieri, G. Colo arXiv: 2601.03763

***A. Cavallin**, F. Marino, JES, In preparation*

Towards semi-exclusive cross-sections



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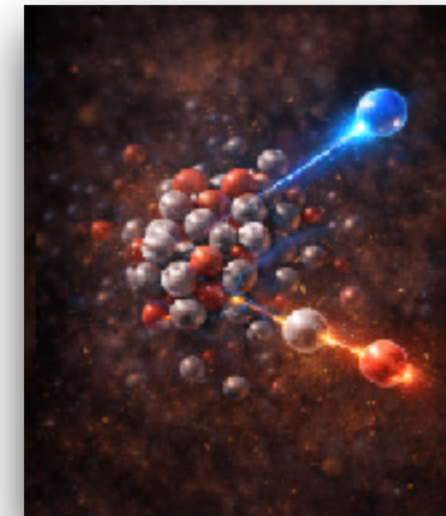
x



Initial nuclear state

Vertex of interaction

Final state interactions

- Quasi-elastic process,
- Pion production,
- Strangeness production
- ...

^{16}O spectral function: probing new physics

Effective Lagrangian (SMEFT):

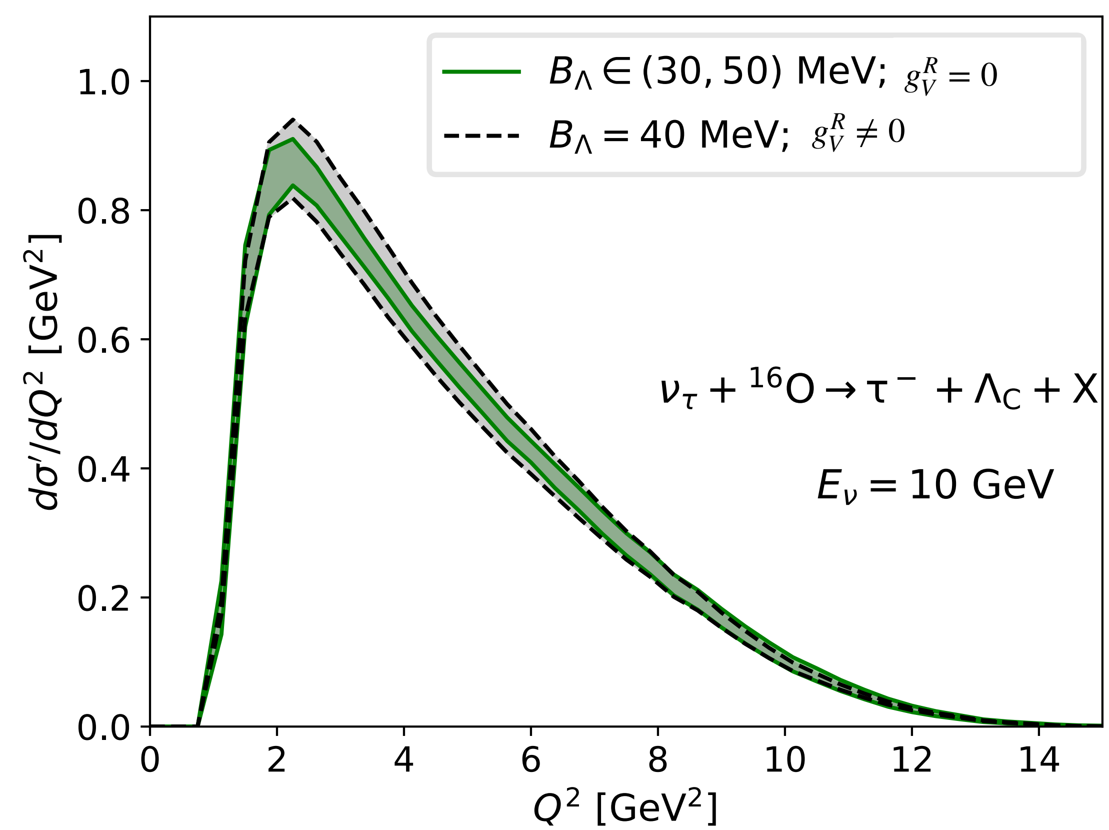
$$\mathscr{L} = -\frac{4G_F}{\sqrt{2}} V_{cd}\left[(1-g_V^L)\mathcal{O}_V^L + g_V^R\mathcal{O}_V^R + g_S^L\mathcal{O}_S^L + g_S^R\mathcal{O}_S^R + g_T^L\mathcal{O}_T^L\right] + h.c.$$

$$\mathcal{O}_V^{L,R} = (\bar{c}\gamma^\mu P_{L,R} d)(\bar{\tau}\gamma_\mu P_L \nu_\tau)$$

$$\mathcal{O}_S^{L,R} = (\bar{c}P_{L,R} d)(\bar{\tau}P_L \nu_\tau)$$

$$\mathcal{O}_T^{L,R} = (\bar{c}\sigma^{\mu\nu} P_L d)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$

- Charge-current transition on the quark level $\nu_\tau d \to \tau^- c$: is there new physics there?
- Constraints on **Wilson coefficients** from experimental observations *(decays of charmed mesons; proton-proton collisions at high energy)*
- Could we constrain them looking at $\nu_\tau n \to \tau^- \Lambda_c$?
- **NEED TO ACCOUNT FOR NUCLEAR EFFECTS:** spectral function for initial nucleon; binding energy for produced Λ_C

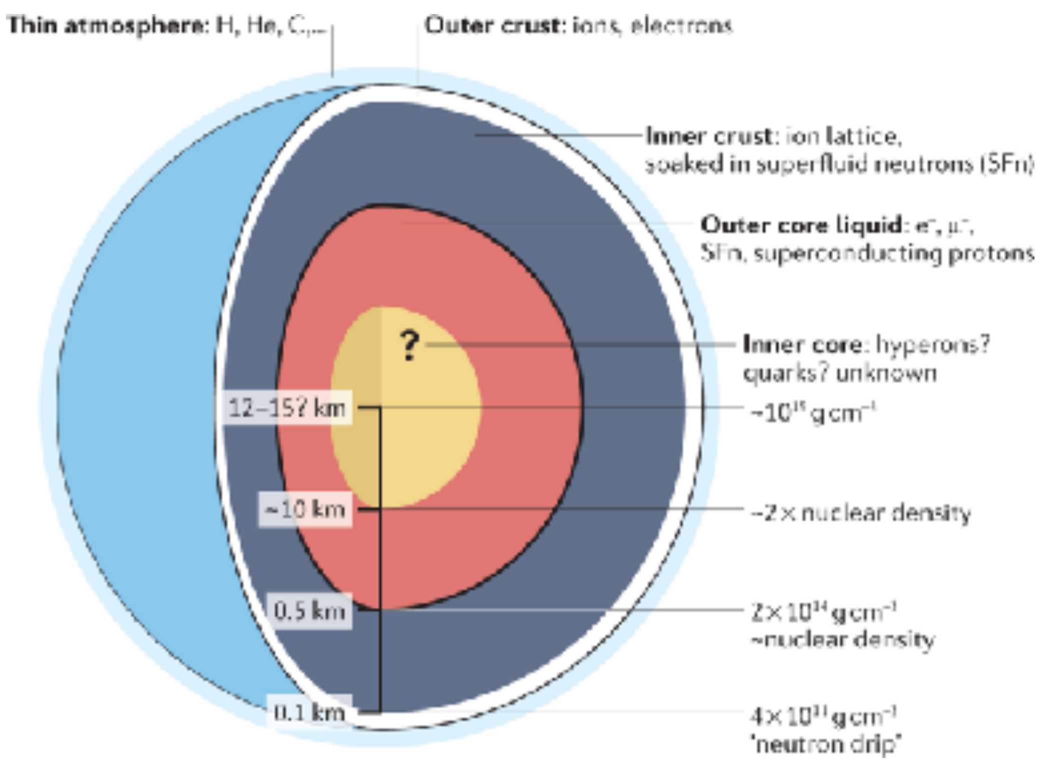


High precision of Λ_C properties in nuclear medium needed to gain sensitivity to BSM

E. Hernandez, J. Nieves, JES, *Phys. Rev. D 112, 053006 (2025)*

Neutrinos in nuclear matter

Neutrinos in nuclear matter



Source: https://www.nature.com/articles/s42254-022-00420-y

What can we learn about neutrino interactions in nuclear matter from first principles?

Spin fluctuation in the long wavelength approximation $q \to 0$

$$S_\sigma(\omega) = \sum_f |\langle \Psi_f | \sigma | \Psi_0 \rangle|^2 \delta(E_0 + \omega - E_f)$$

- ✓ Neutrino interaction rate driven by nuclear responses
- ✓ neutrino emission — mechanism of cooling in neutron stars
- ✓ Dynamics of supernova core collapse

Neutrinos in PNM

PHYSICAL REVIEW C **87**, 025802 (2013)

Spin response and neutrino emissivity of dense neutron matter

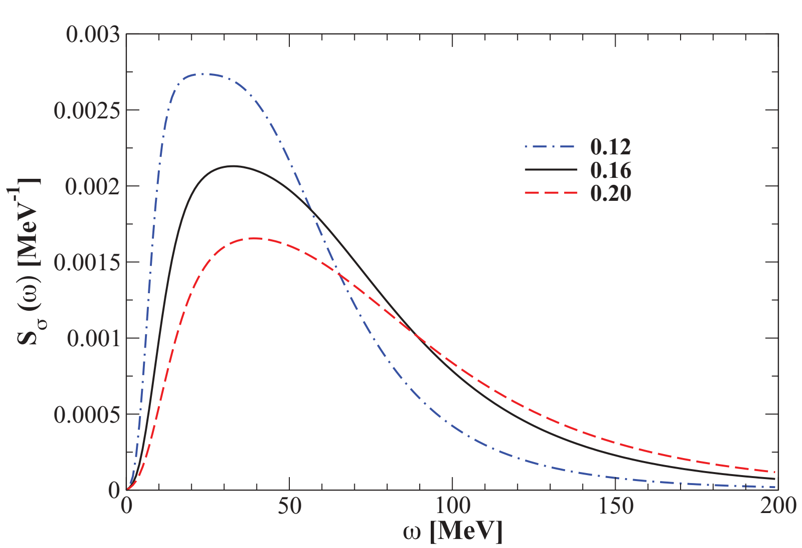
G. Shen,[1] S. Gandolfi,[1] S. Reddy,[1,2] and J. Carlson[1]
[1]*Theoretical Division, Los Alamos National Laboratory, New Mexico 87545, USA*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195, USA*
(Received 29 May 2012; published 15 February 2013)

- Response reconstructed from 3 energy-weighted sum-rules

$$Q^n_\sigma = \int d\omega\, \omega^n S_\sigma(\omega)$$

$$n = -1,\ 0,\ 1$$

- AFDMC calculation, using AV8'



$$Q^0_\sigma = 1 + \lim_{q\to 0} \frac{4}{3N} \sum_{i\neq j}^{N} \langle 0 | e^{-iq(r_i - r_j)} \sigma_i \cdot \sigma_j | 0 \rangle$$

(Expectation value of 2-body operator)

$$Q^1_\sigma = -\frac{4}{3N} \lim_{q\to 0} \langle 0 | [H_N, s(q)] \cdot s(-q) | 0 \rangle$$

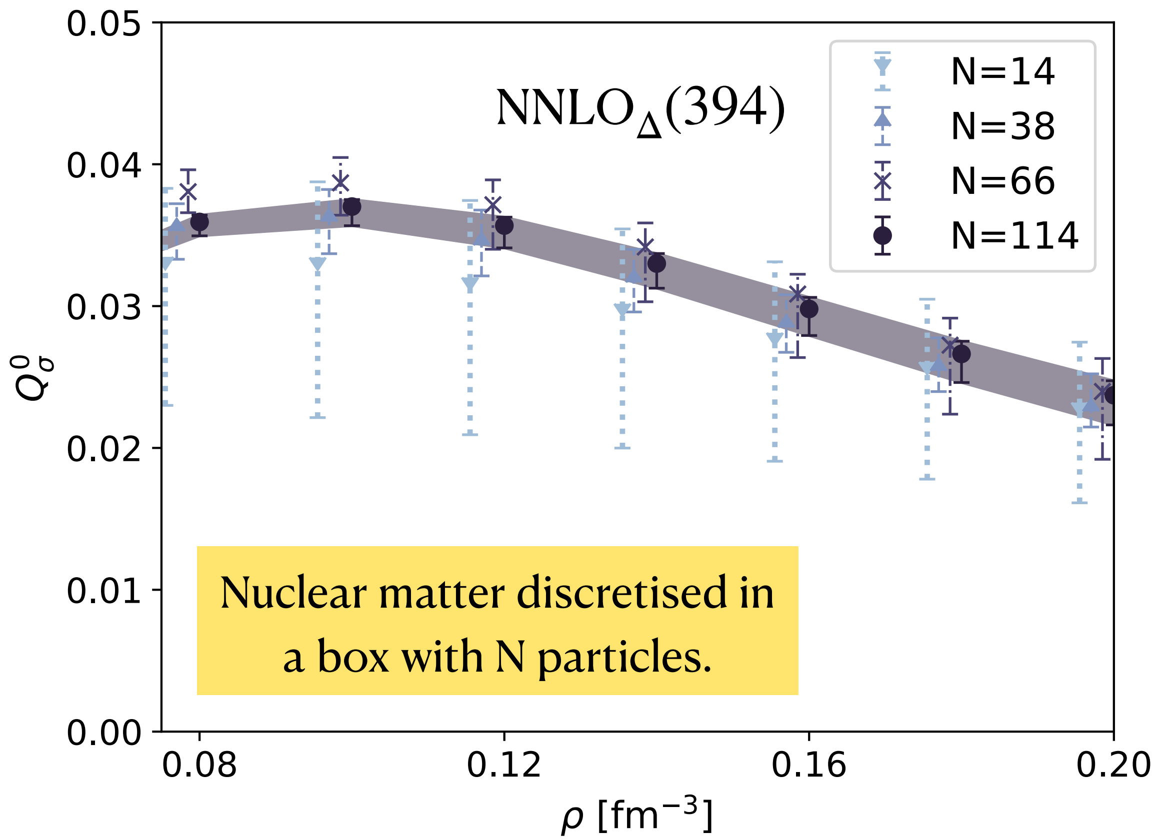
(Sensitive to tensor and spin-orbit part of Hamiltonian)

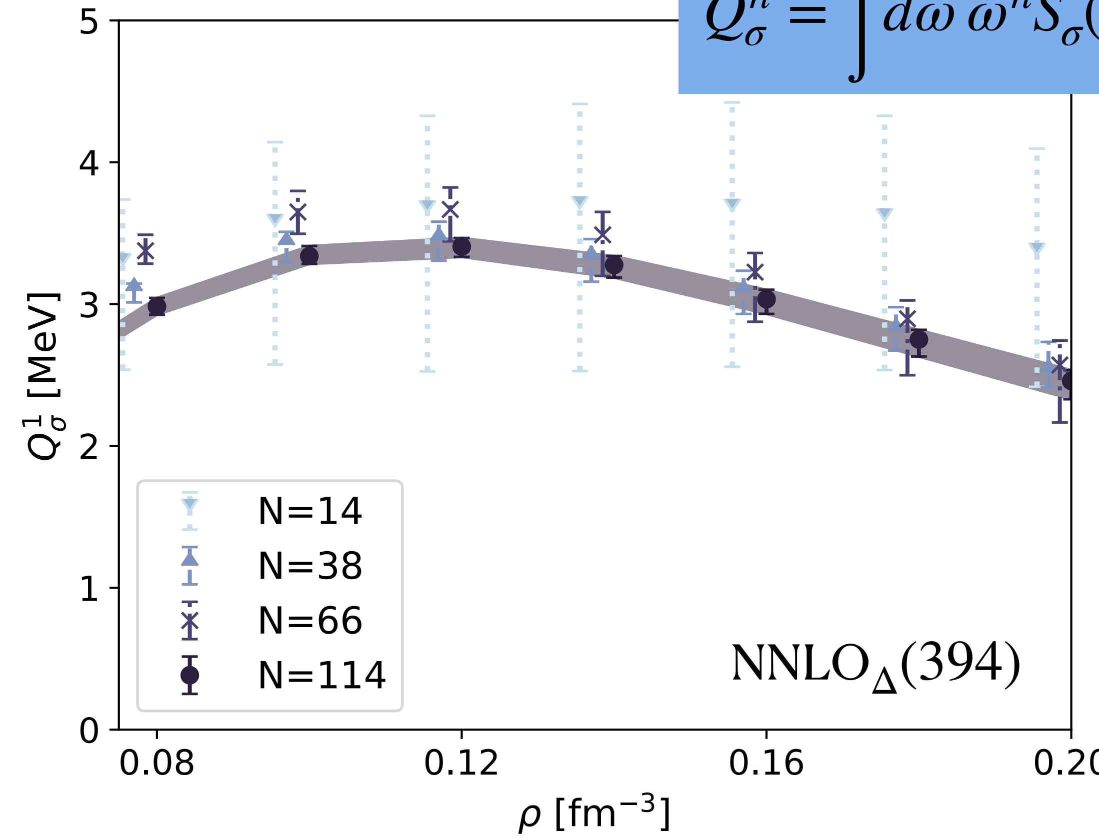
$$\mathbf{s}(t,q) = V^{-1} \sum_{i=1}^{N} e^{-i\boldsymbol{q}\cdot\boldsymbol{r}_i(t)} \boldsymbol{\sigma}_i$$

Neutrinos in nuclear matter

Coupled cluster + NNLO$_\Delta$(394) interaction

$$Q^n_\sigma = \int d\omega\, \omega^n S_\sigma(\omega)$$





J.E.S., W.Jiang, A. Roggero, *Phys. Rev. Lett.* 134, 192701 (2025)

Sum rules calculation consistent between simulations with various N

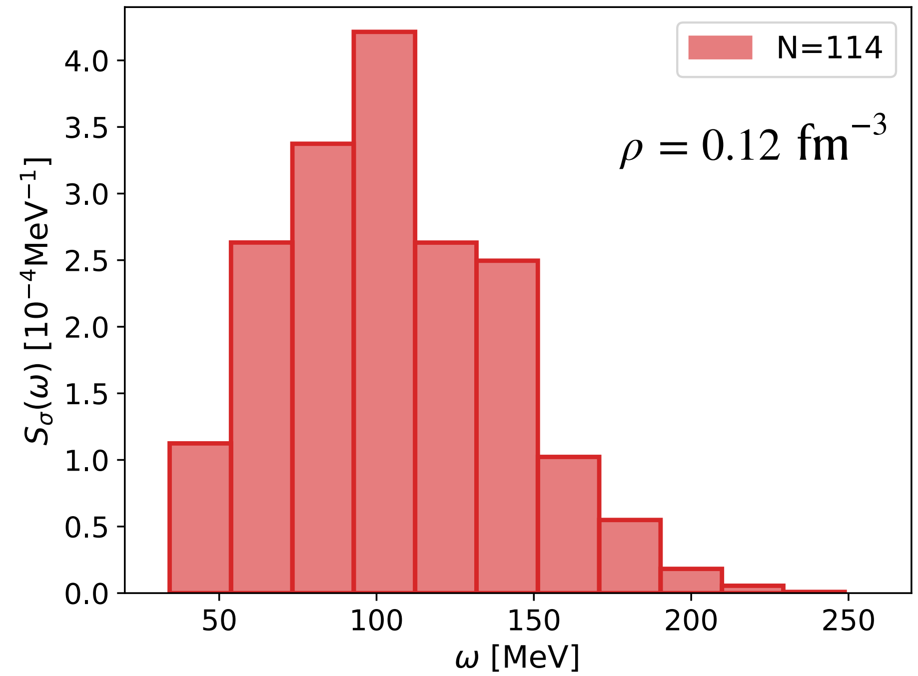
But very different from AV8 results

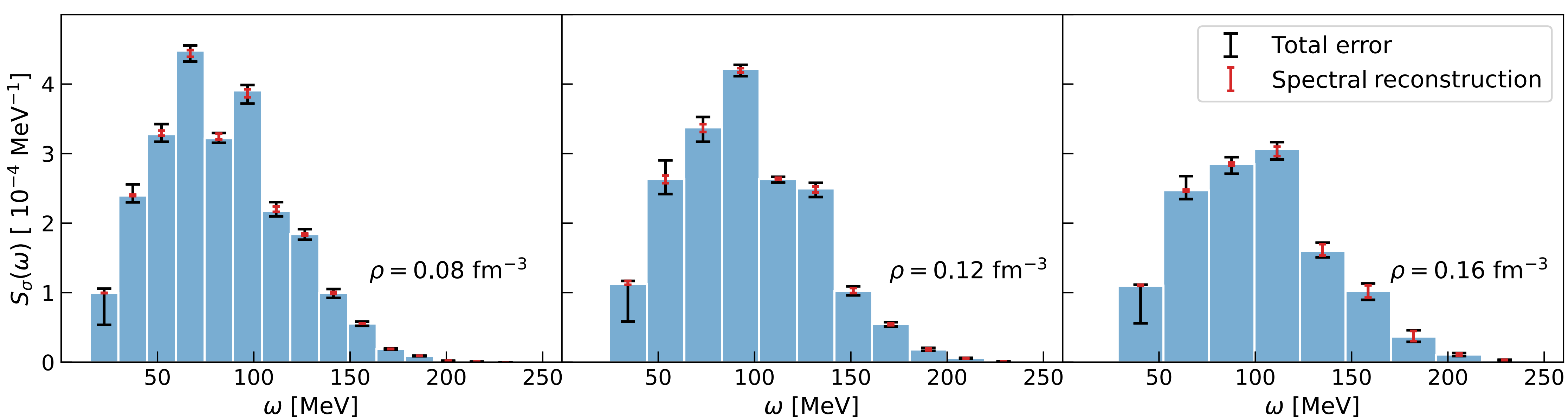
Density (fm^{-3})	S_σ^{-1} (MeV^{-1})	S_σ^0	S_σ^{+1} (MeV)
$n = 0.12$	0.0057(9)	0.20(1)	8(1)
$n = 0.16$	0.0044(7)	0.20(1)	11(1)
$n = 0.20$	0.0038(6)	0.18(1)	14(1)

Neutrinos in PNM

Coupled cluster + Gaussian integral transform

We have tools to get access to the excited spectrum and reconstruct it using **Gaussian integral transform**

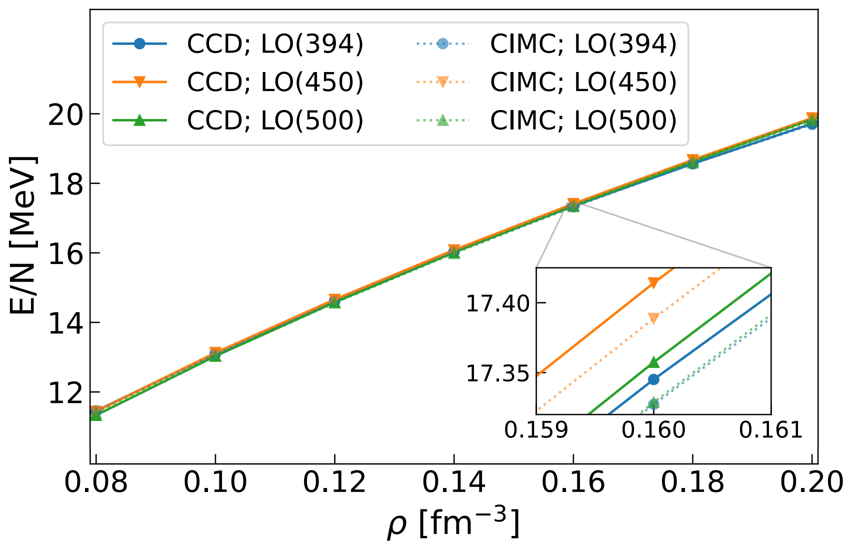




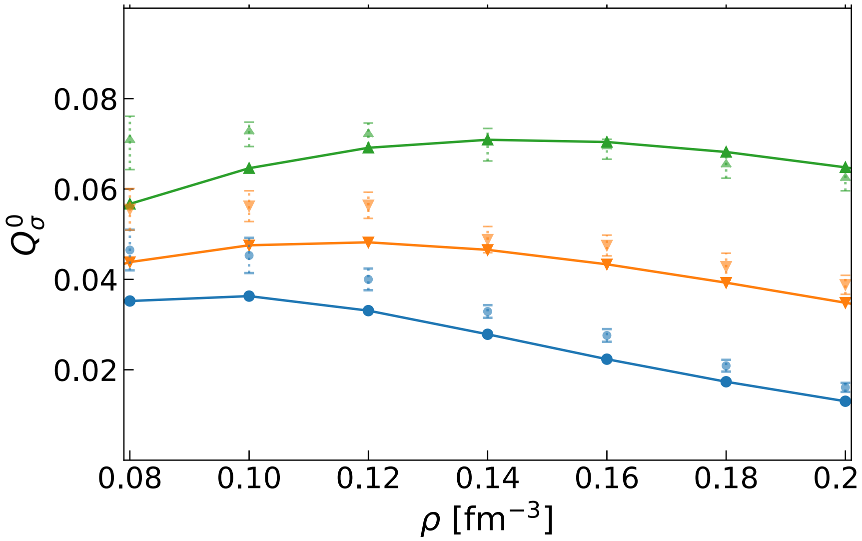
J.E.S., W.Jiang, A. Roggero, *Phys. Rev. Lett.* 134, 192701 (2025)

Neutrinos in nuclear matter

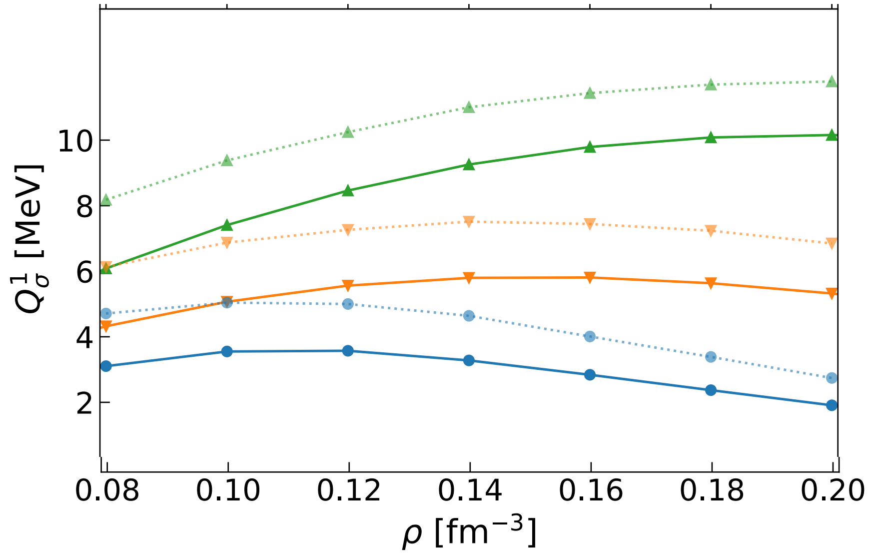
How sensitive to nuclear Hamiltonian & wave function?



Energy per particle



Total strength of spin response



Energy-weighted sum-rule
of spin response

Spin response is a highly sensitive observable (strongly depends on correlations in wave function and nuclear Hamiltonian)

Outlook

- Neutrino-nucleus scattering
  - Towards ^{40}Ar
  - Include 2-body currents
  - Spectral function -> towards pion production regime
- Nuclear matter:
  - Spin response sum-rules: Hamiltonian dependence + other many-body methods
  - Include temperature dependence
  - Momentum-dependent responses

Thanks to all collaborators

- @ Chalmers: **A. Cavallin**
- @ JGU: S. Bacca, W. Jiang, F. Marino, **I. Reis**
- @ ORNL&UTK: G. Hagen, T. Papenbrock
- @ Univ. of Valencia: J. Nieves, N. Rocco, A. Lovato
- @ Univ. of Salamanca: E. Hernandez
- @ Univ. of Trento: A. Roggero

and thank you for attention!

BACKUP

More on QMC

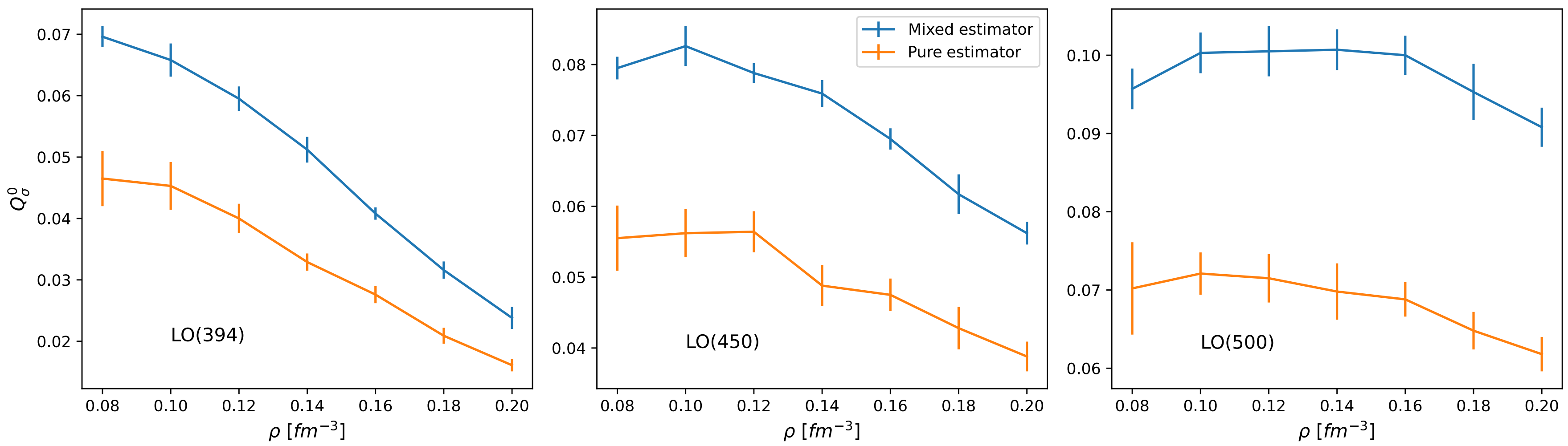
- Mixed estimator:

$$\langle O\rangle_M = \frac{\langle\Psi_T|O|\Psi(\tau)\rangle}{\langle\Psi_T|\Psi(\tau)\rangle} = \frac{\langle\Psi_T|Oe^{-\tau H}|\Psi_T\rangle}{\langle\Psi_T|e^{-\tau H}|\Psi_T\rangle} \xrightarrow{\tau\to\infty} = \frac{\langle\Psi_T|O|\Psi_0\rangle}{\langle\Psi_T|\Psi_0\rangle}$$

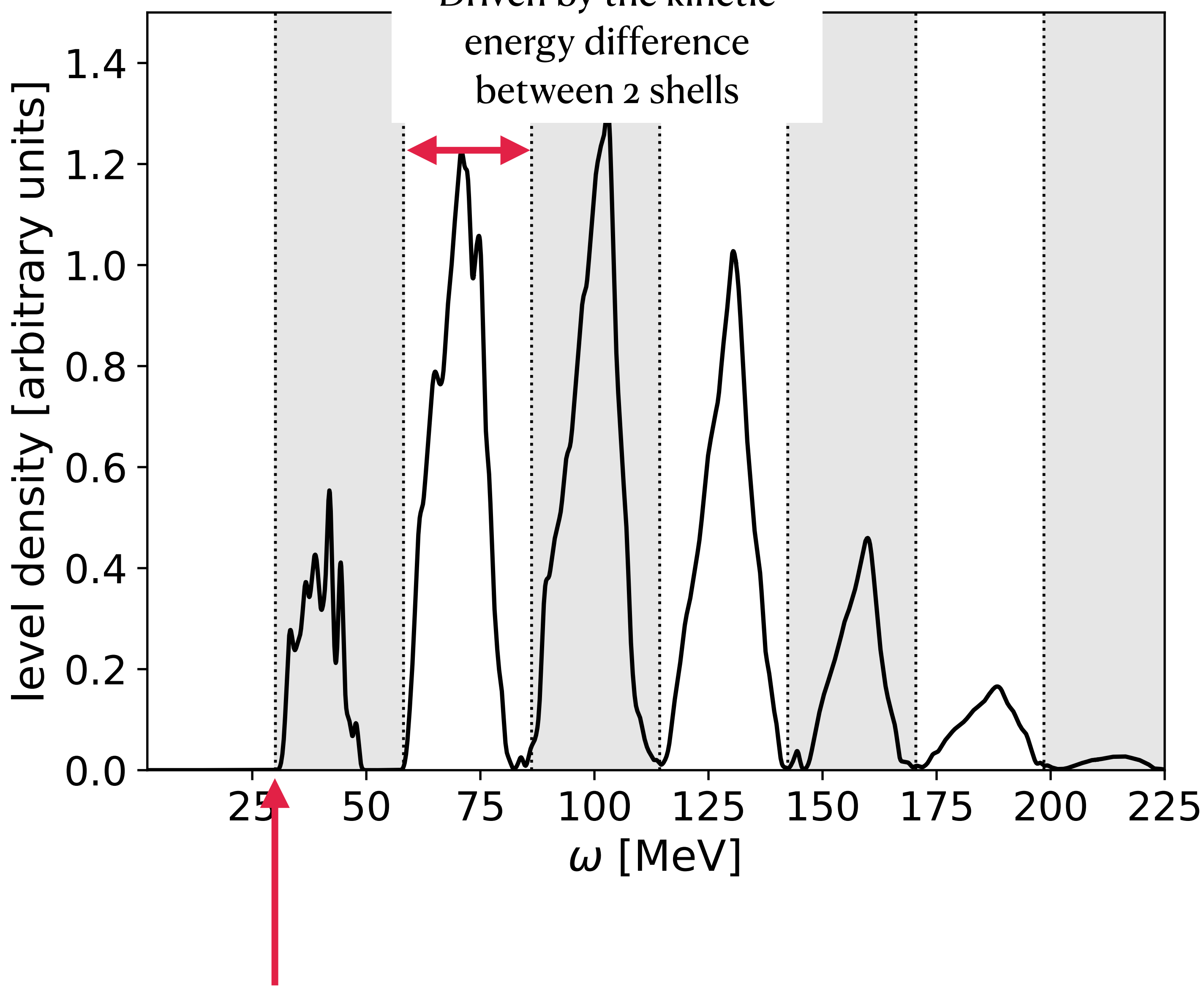
- For observables commuting with Hamiltonian:

$$\langle O\rangle_M = \frac{\langle\Psi_T|O|\Psi(\tau)\rangle}{\langle\Psi_T|\Psi(\tau)\rangle} = \frac{\langle\Psi_T|e^{-\tau H/2}Oe^{-\tau H/2}|\Psi_T\rangle}{\langle\Psi_T|e^{-\tau H/2}e^{-\tau H/2}|\Psi_T\rangle} \xrightarrow{\tau\to\infty} = \frac{\langle\Psi_0|O|\Psi_0\rangle}{\langle\Psi_0|\Psi_0\rangle} = \langle O\rangle_0.$$

- There is a systematic error which we can quantify for Q_σ^0



Binning in nuclear matter



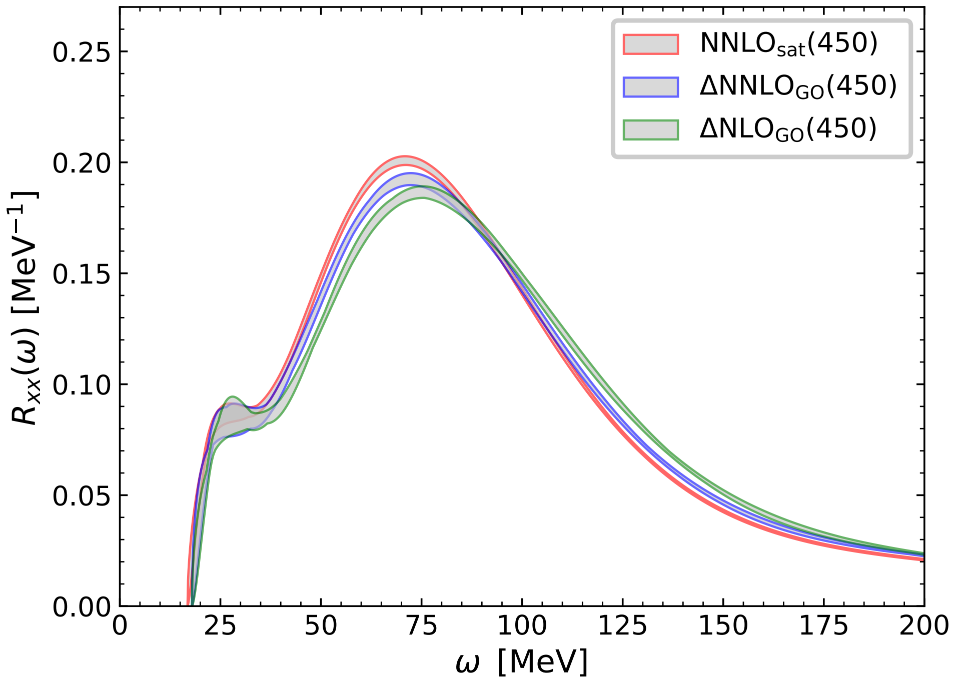
$$E_{gap} = \frac{\hbar^2 (2\pi/L)^2}{2m}$$

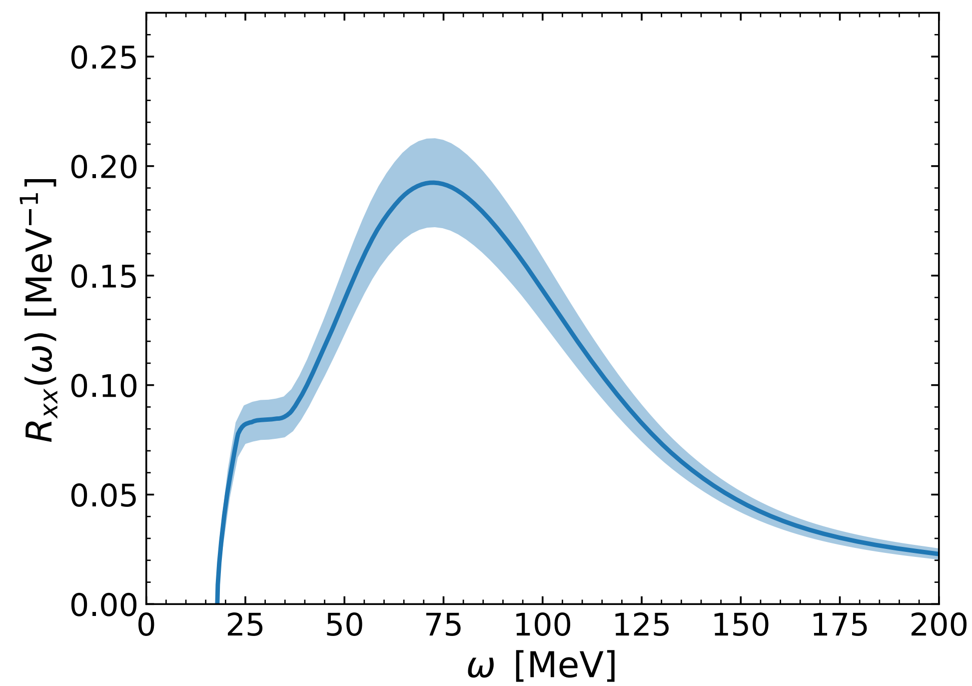
Size of the box: $L = (N/\rho)^{1/3}$

First excitation:
Energy needed to excite 2 nucleons from the 1st closed-shell configuration
~kinetic energy ~$(\rho/N)^{2/3}$

Uncertainty estimation (responses)

Assessing EFT truncation error





Gaussian process (GP) to assess chiral truncation using 2 orders of expansion

Order k EFT prediction: $y_k(p) = y_{\text{ref}}(p) \sum_{n=0}^{k} c_n(p) \left(\frac{p}{\Lambda}\right)^n$

EFT truncation error: $\delta y_k(p) = y_{\text{ref}}(p) \sum_{n=k+1}^{\infty} c_n(p) \left(\frac{p}{\Lambda}\right)^n$

Draws from an underlying GP

Bayesian neural network

$$P(\mathcal{W}|Y) = \frac{P(Y|\mathcal{W})P(\mathcal{W})}{P(Y)}$$

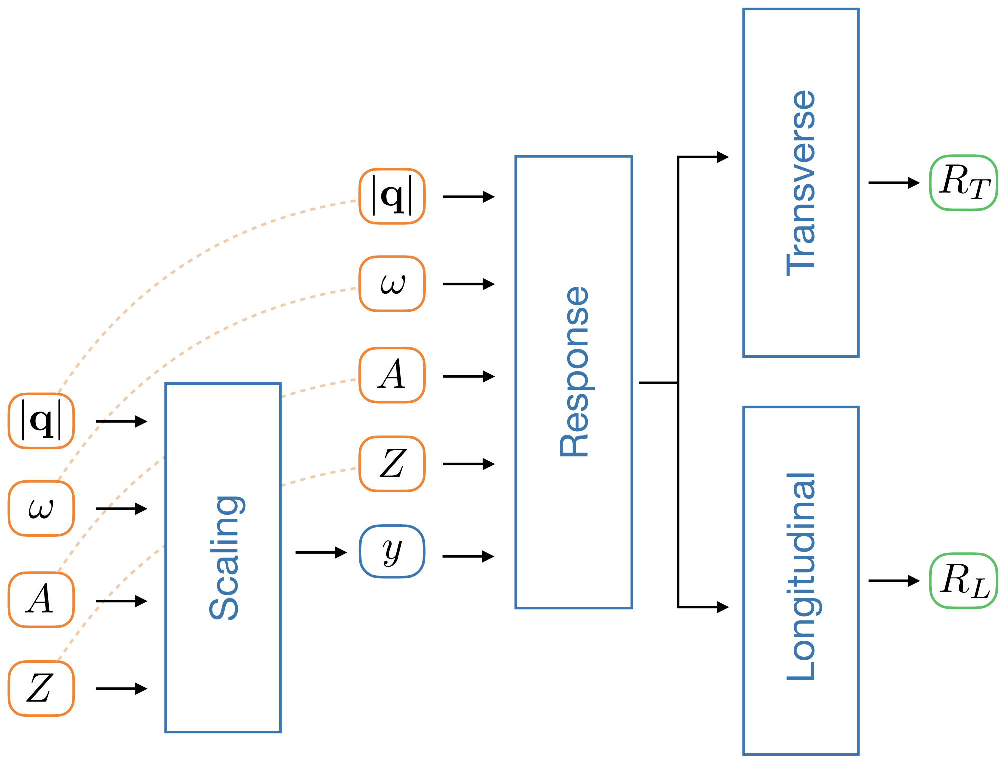
$\mathcal{W} = w_1, \ldots, w_{N_p}$ - parameters of BNN treated as probability distribution

Using the Gaussian prior:

$$P(\mathcal{W}) = \frac{1}{(2\pi)^{N_p/2}} \exp\left(\sum_{i=1}^{N_p} -\frac{w_i^2}{2}\right)$$

Assume a Gaussian for the likelihood

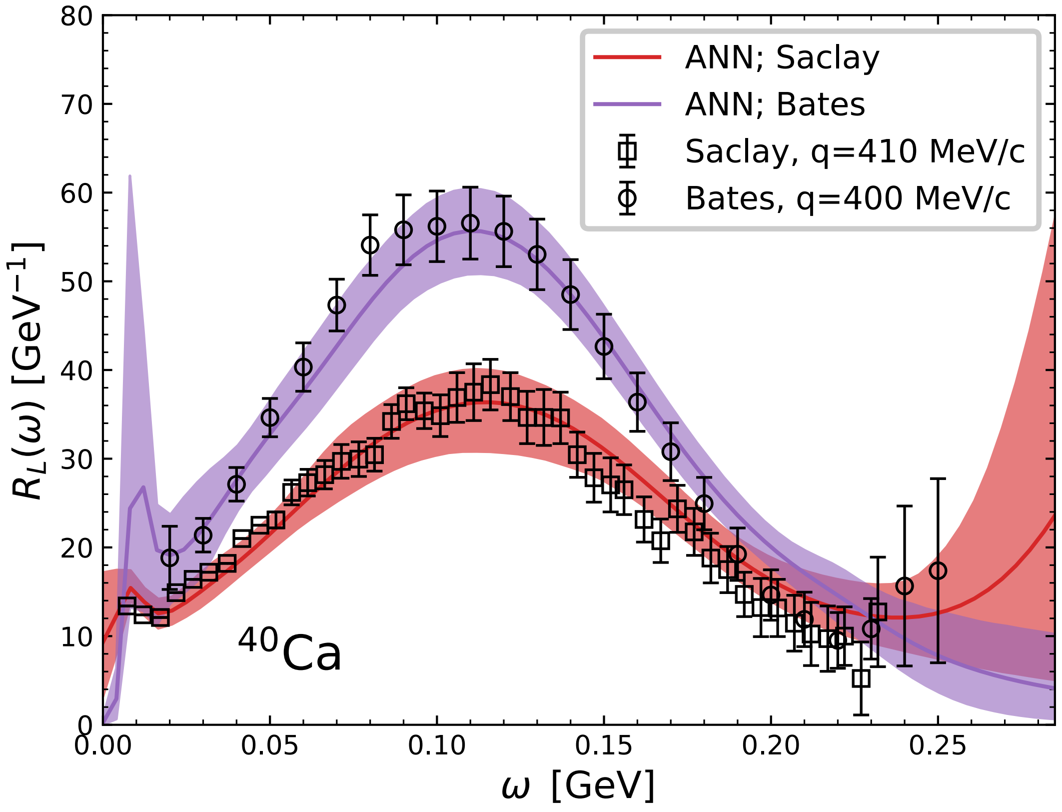
$$P(Y|\mathcal{W}) = \exp\left(-\frac{\chi^2}{2}\right)$$

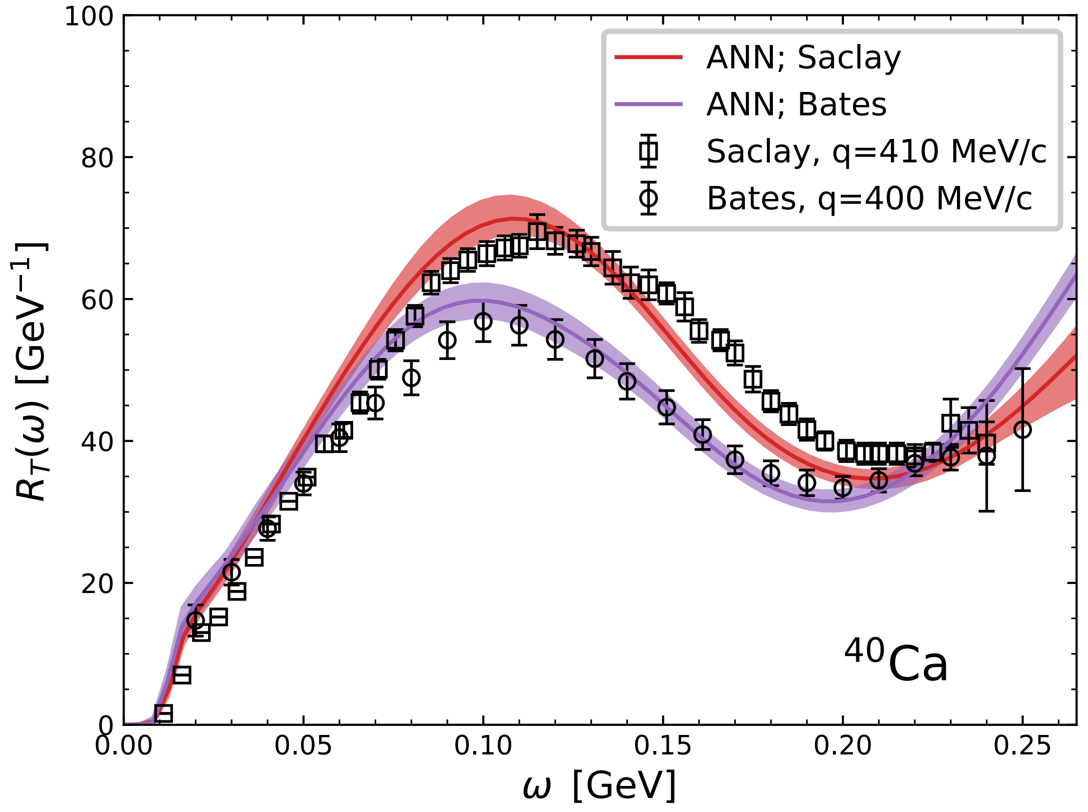


The loss function is the least-squares fit to data

$$\chi^2 = \sum_{i=1}^{N_t} \frac{\left[y_i - \hat{y}_i(\mathcal{W})\right]^2}{\sigma_i^2}$$

BNN responses on ^{40}Ca





BNN responses on ^{40}Ca