Neutrino-nucleus interactions for oscillation experiments

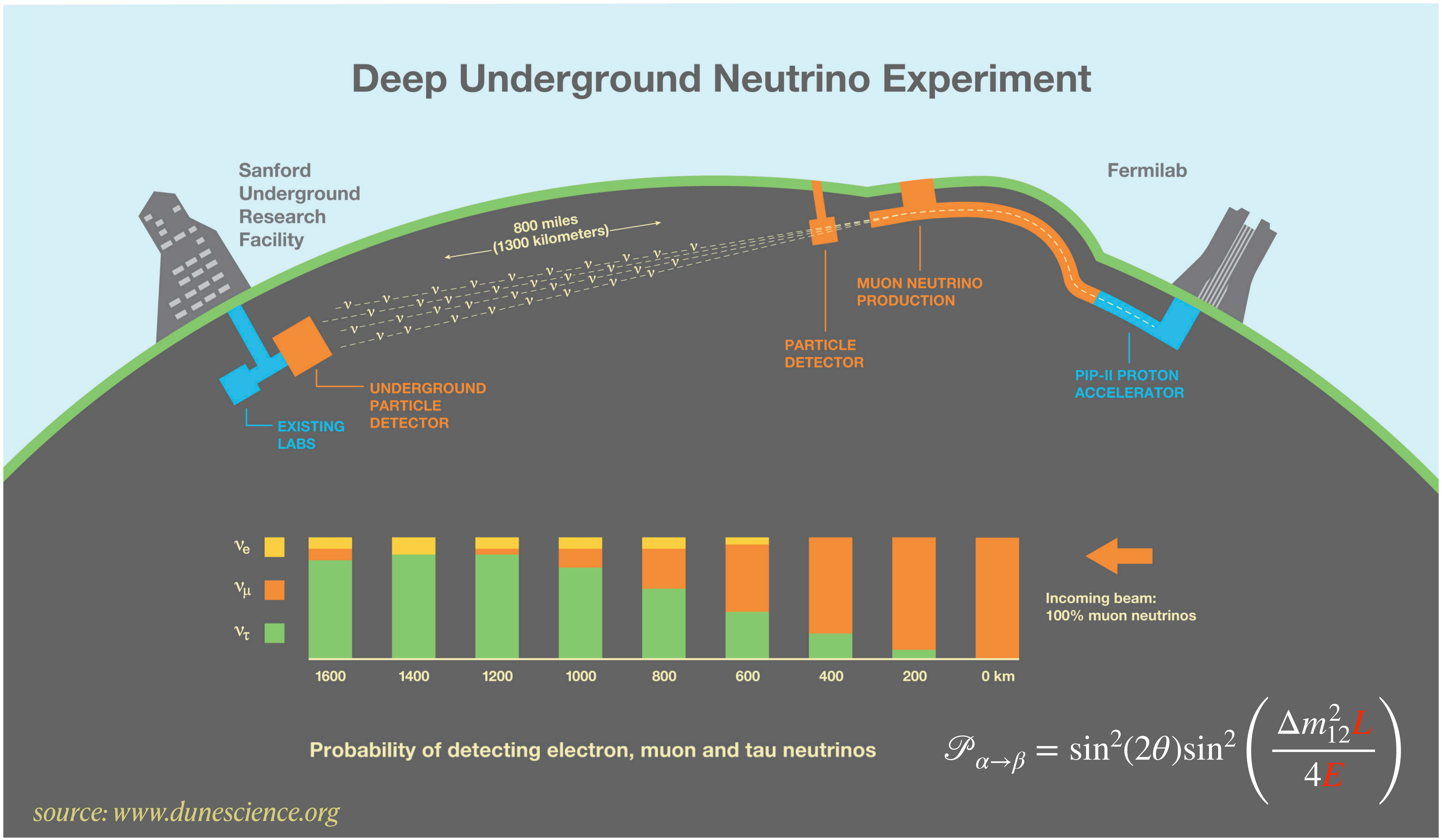
Joanna Sobczyk

29 May 2025

CHALMERS
UNIVERSITY OF TECHNOLOGY

Hadrons CRC 1660 Nuclei

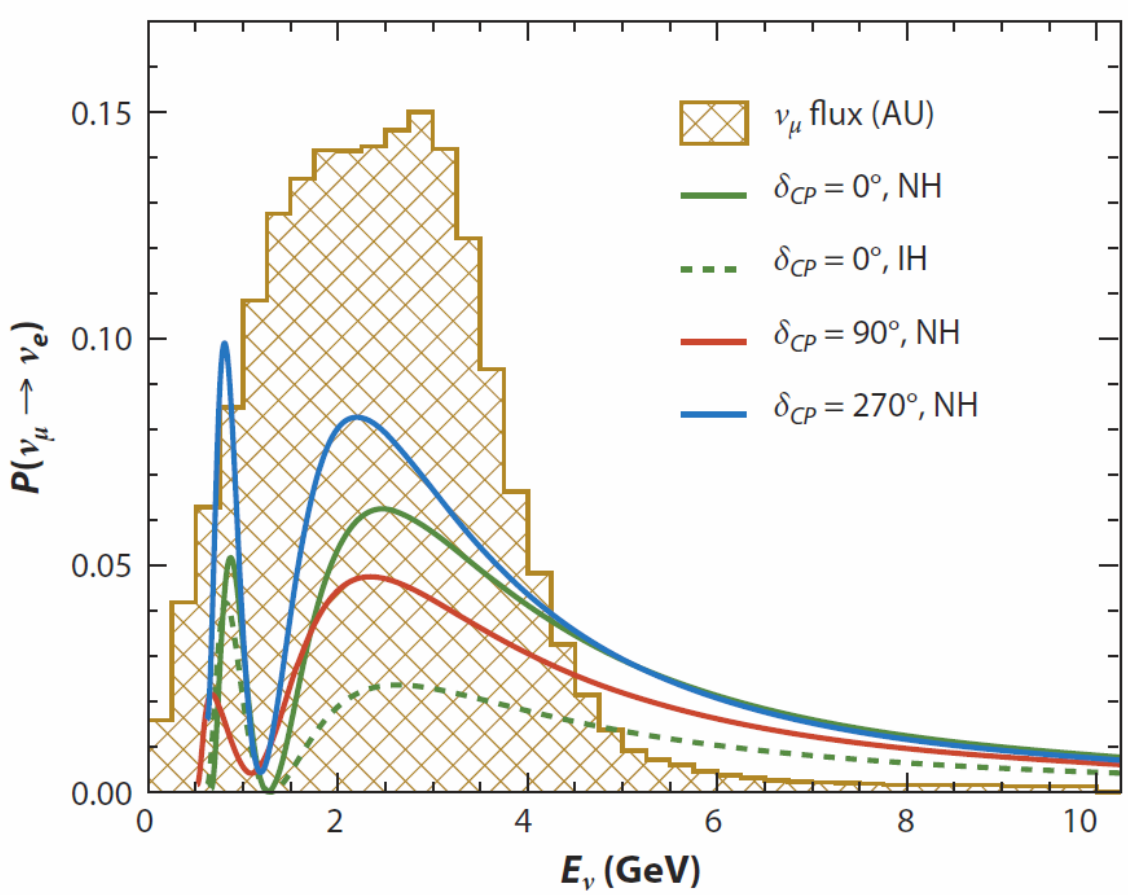
Neutrino oscillations



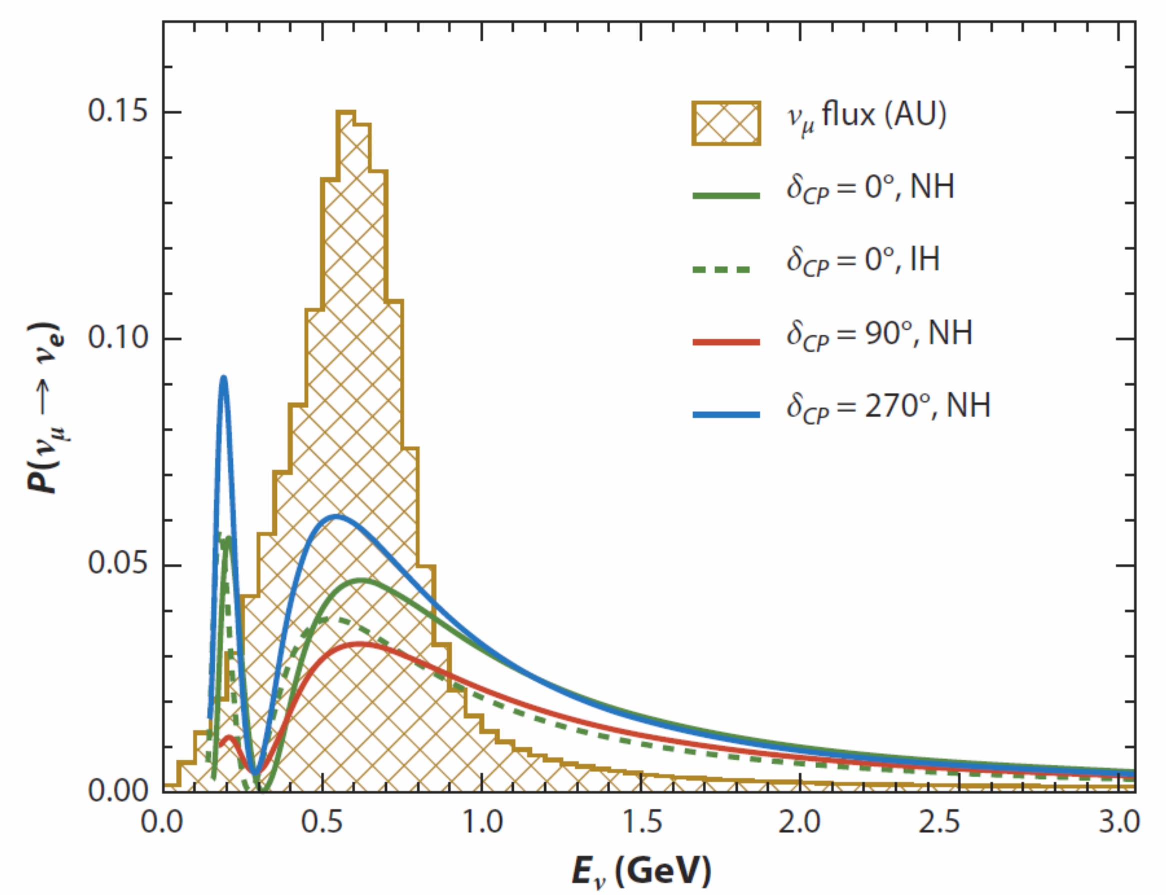
$$\mathscr{P}_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)$$

Aims & challenges

DUNE



HyperK



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

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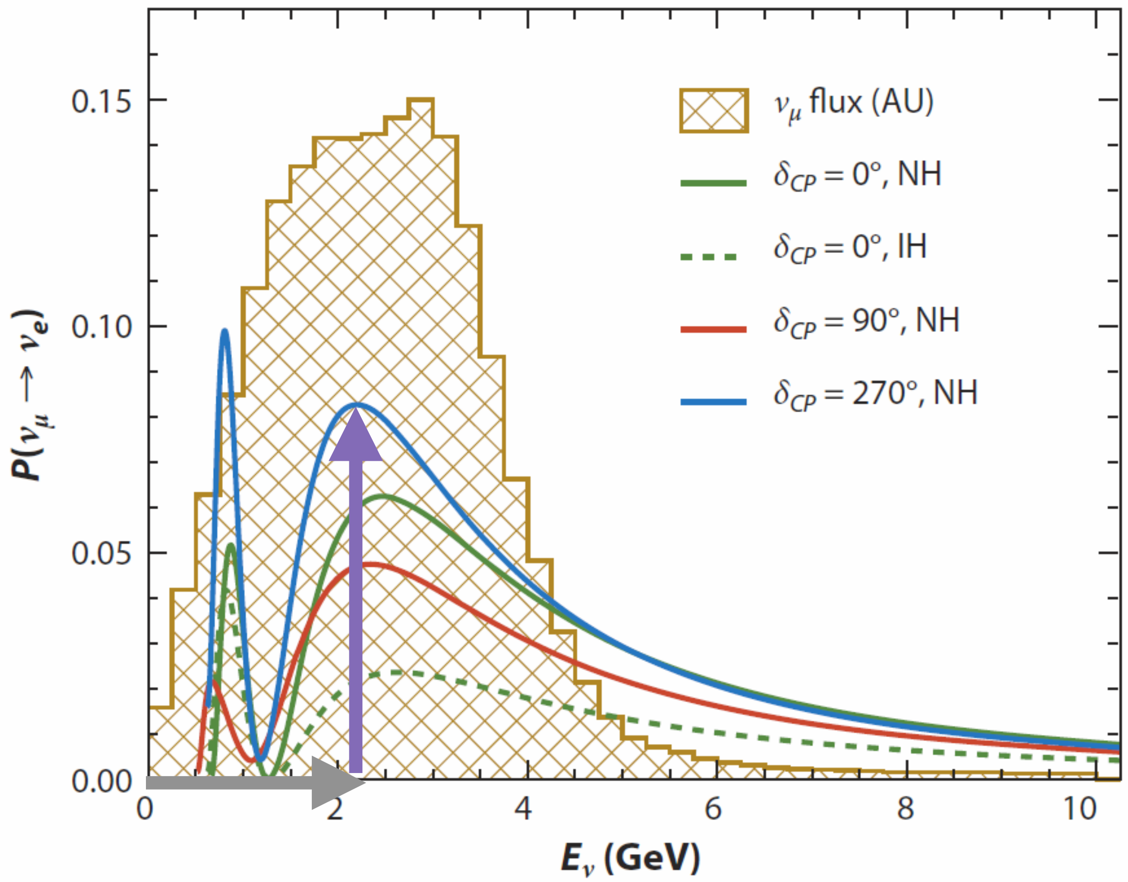
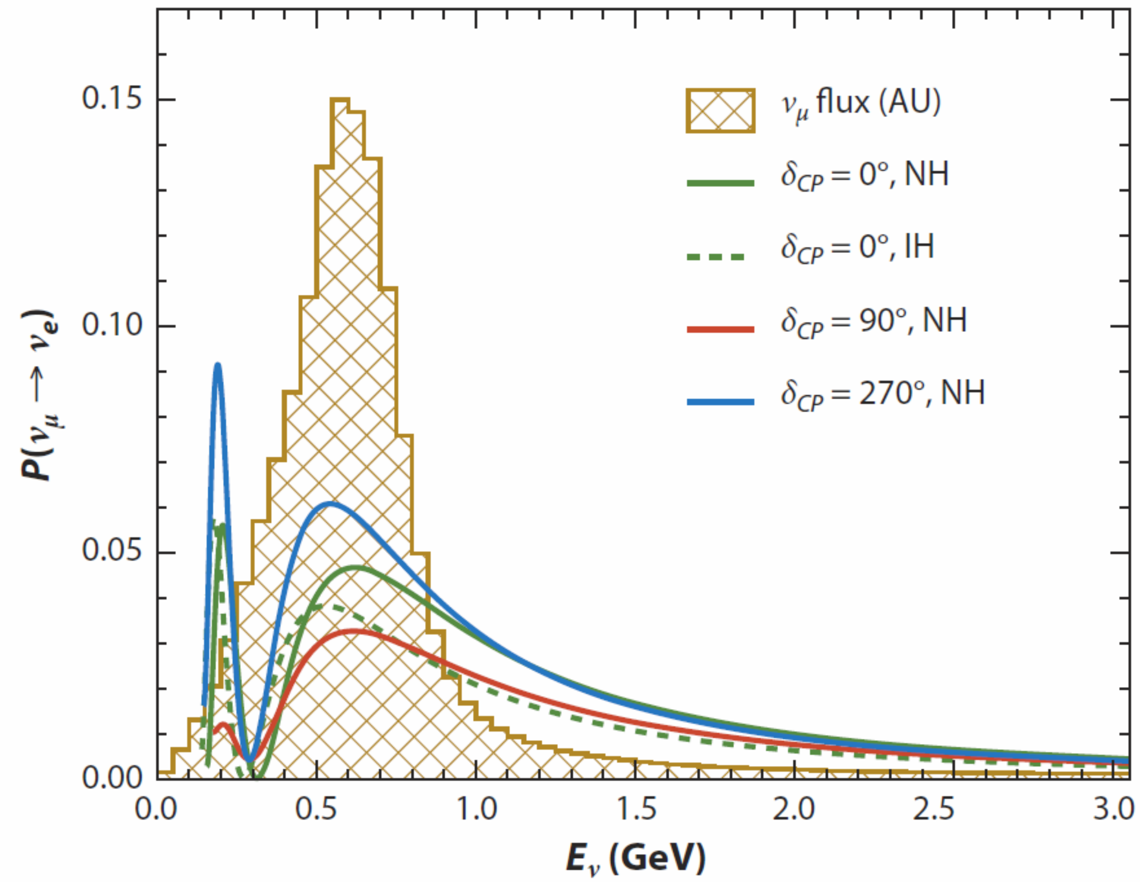


Position of the oscillation peak depends on energy reconstruction

HyperK



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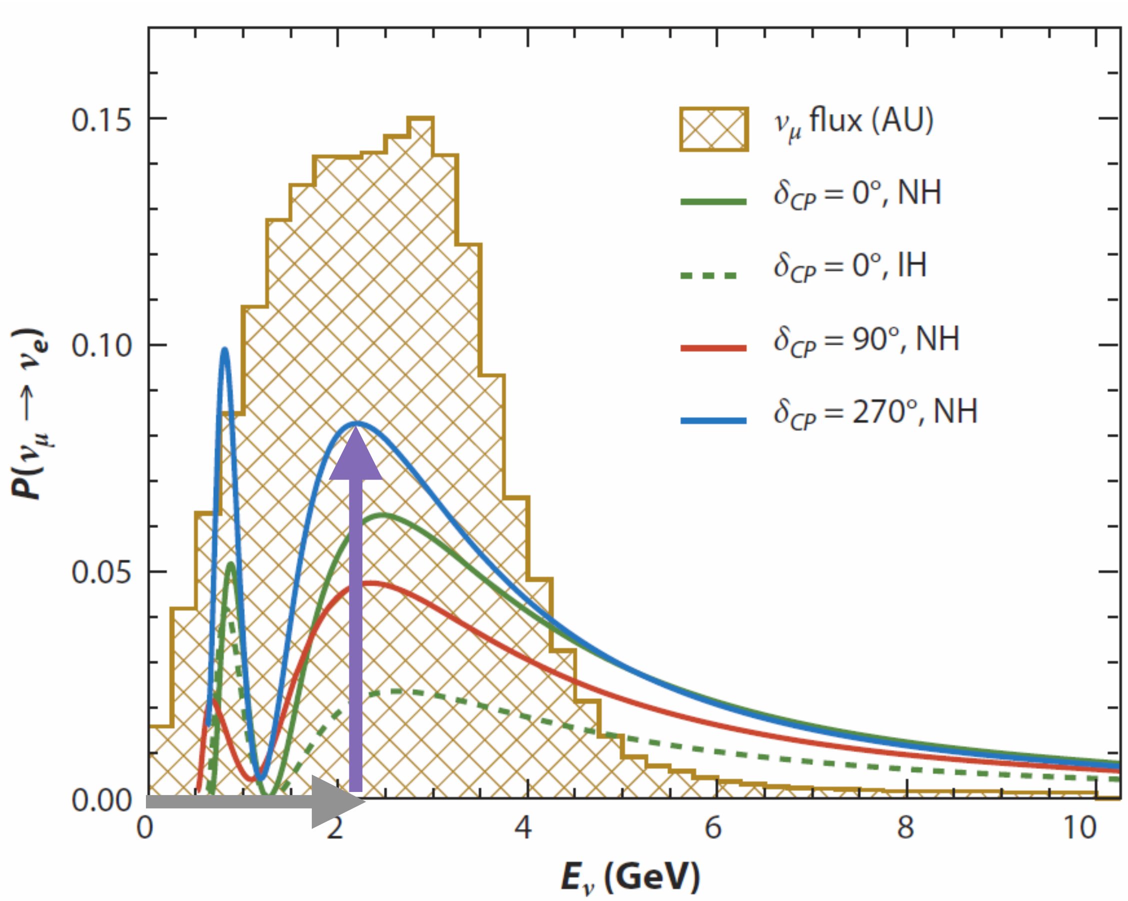

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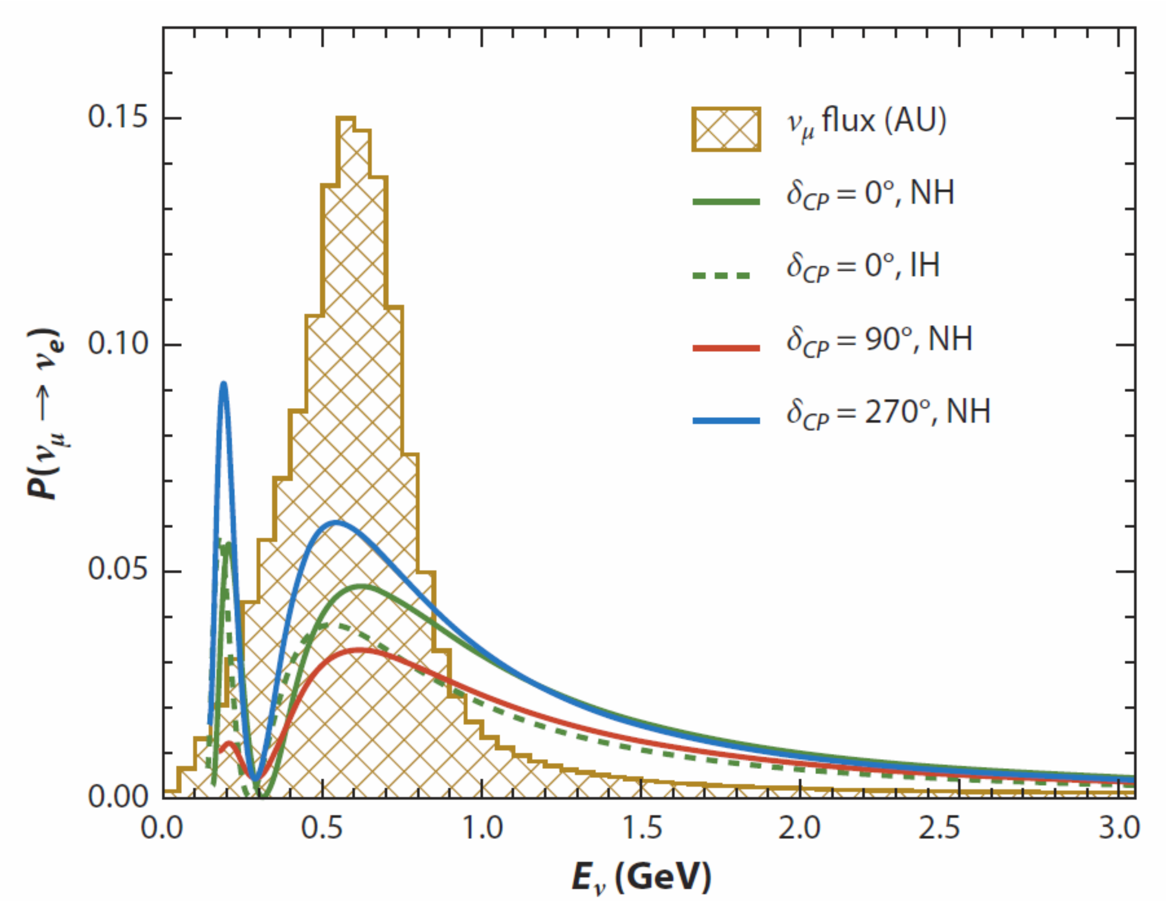
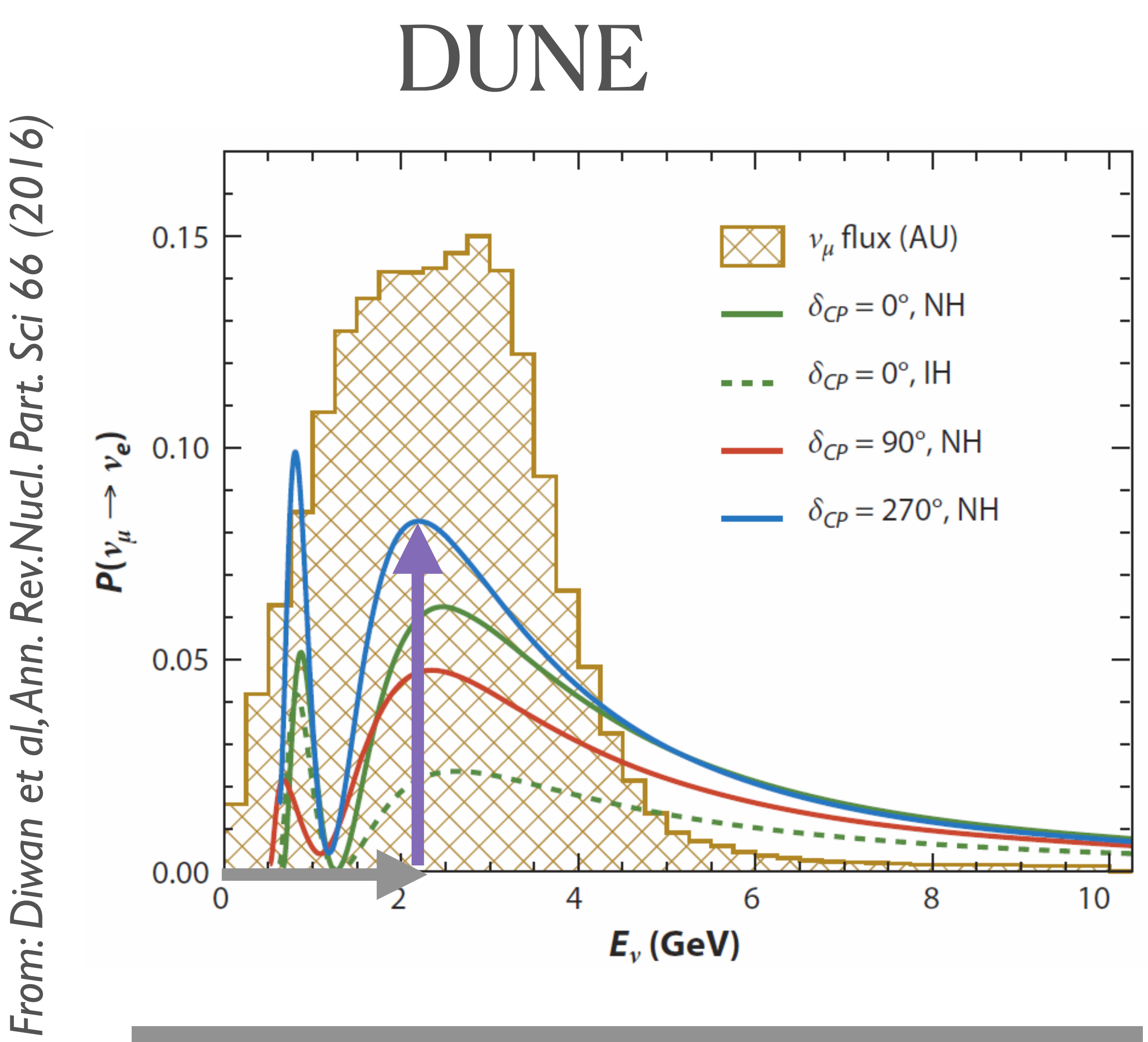
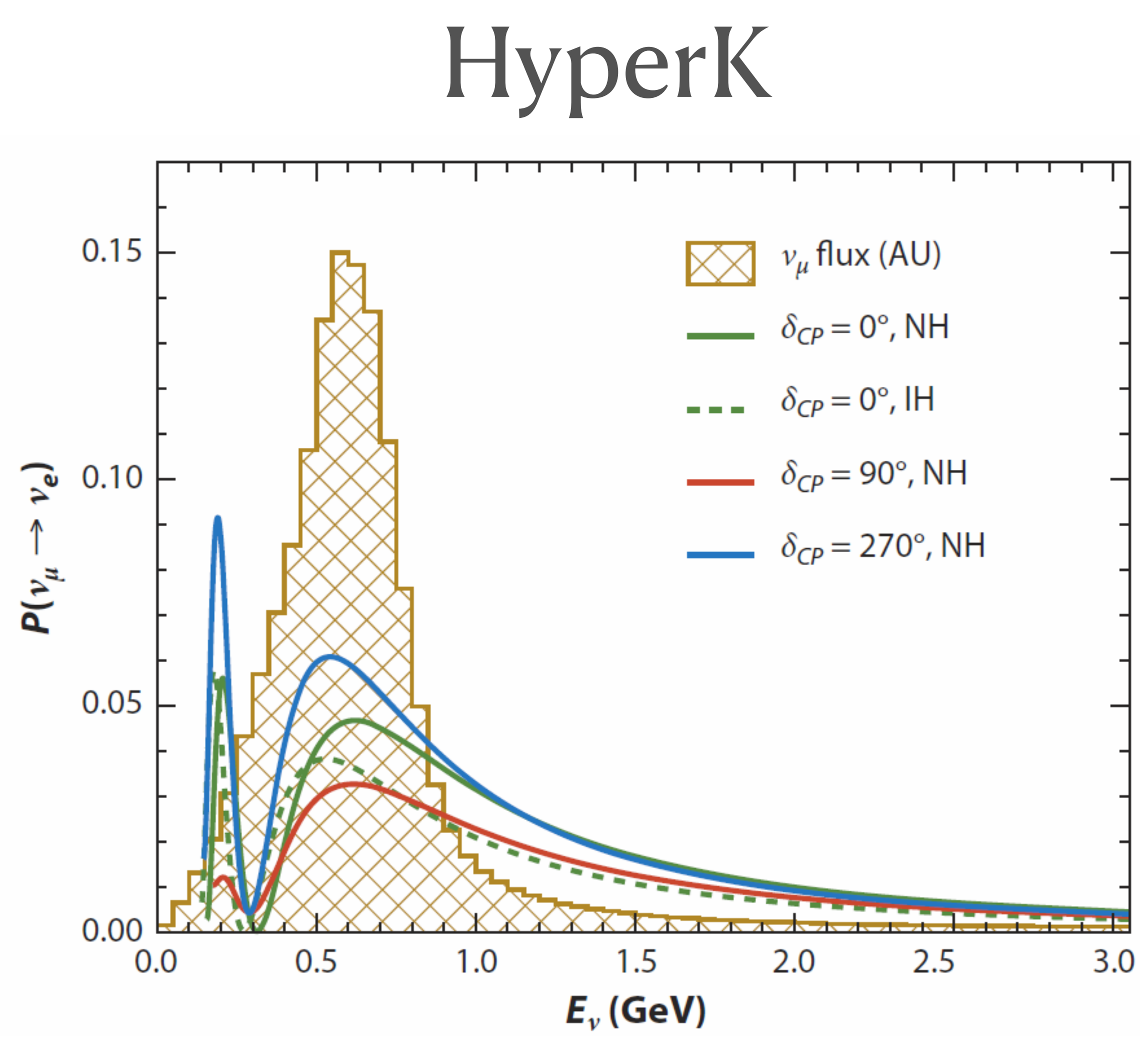


DUNE aims at uncertainties < 1% meaning O(25 MeV) precision of energy reconstruction

Aims & challenges





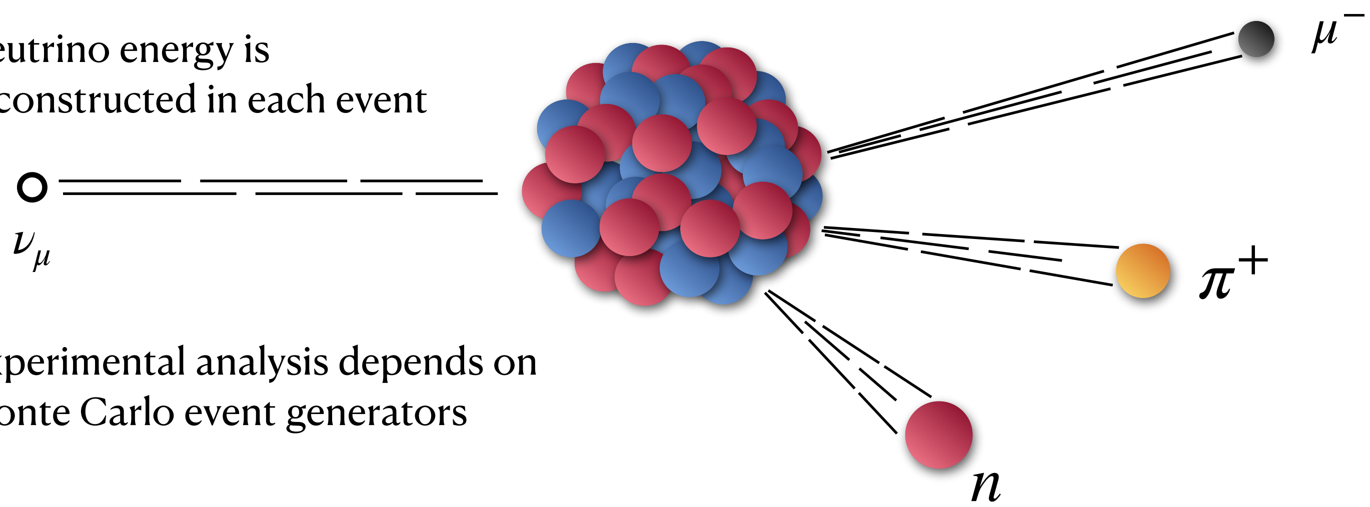
Position of the oscillation peak depends on energy reconstruction

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

Systematic errors should be small since statistics will be high.

Motivation

Neutrino energy is
reconstructed in each event



Experimental analysis depends on
Monte Carlo event generators

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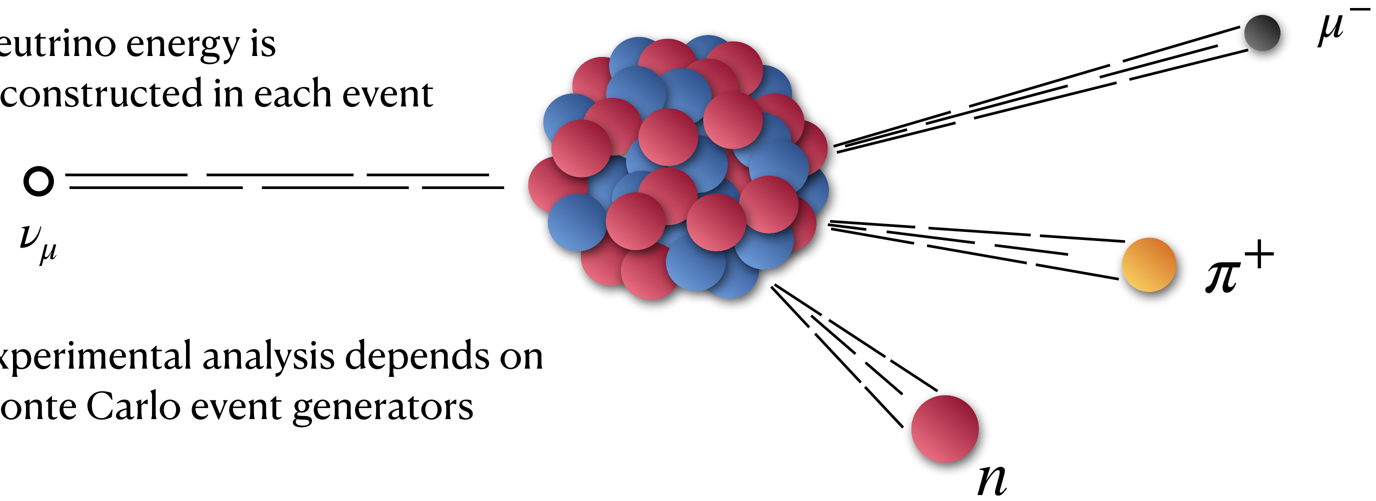
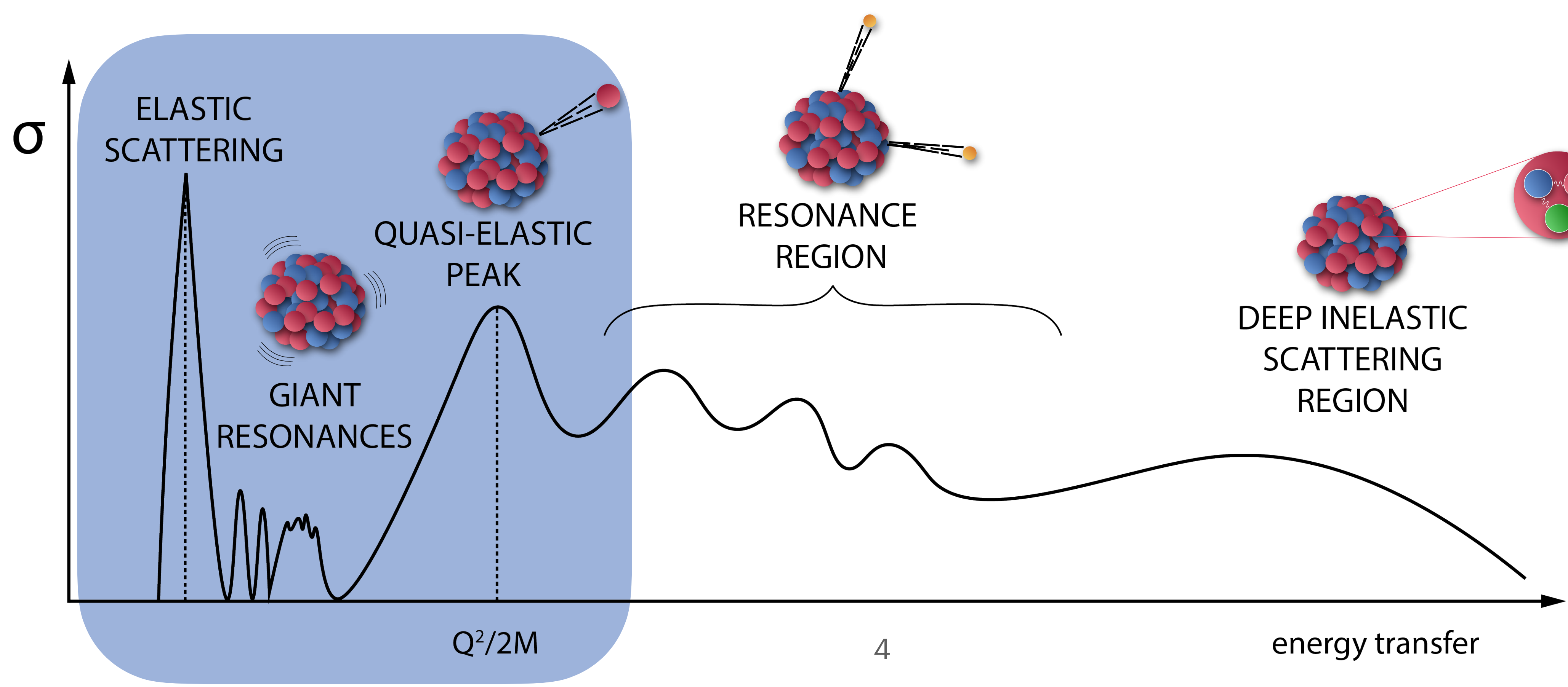


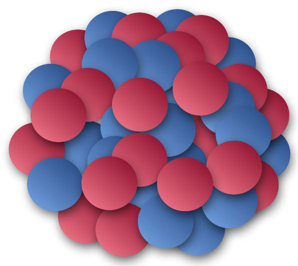
Experimental analysis depends on Monte Carlo event generators

WHAT CAN WE LEARN FROM A (MORE) FUNDAMENTAL THEORY?



"Ab initio" nuclear theory

nucleons — degrees of freedom



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

$$\mathscr{H} = \sum_{i=1}^{A} t_{kin} + \sum_{i>j=1}^{A} v_{ij} + \sum_{i>j>k=1}^{A} v_{ijk} + \ldots$$

“Ab initio” nuclear theory

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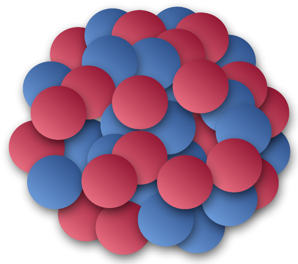

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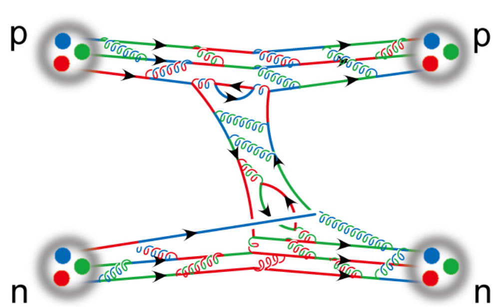
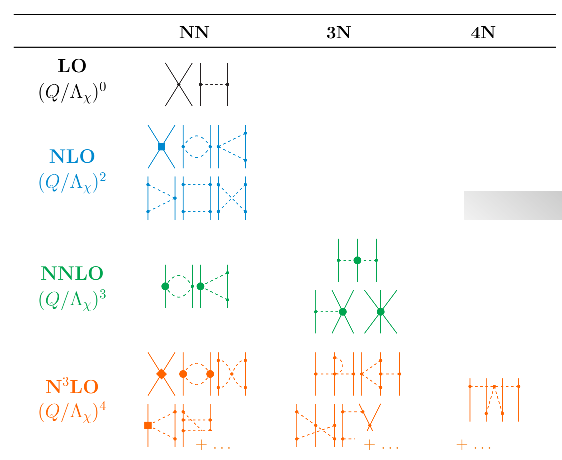
How the **nuclear force** is rooted in the fundamental theory of QCD?

Quantum Chromodynamics



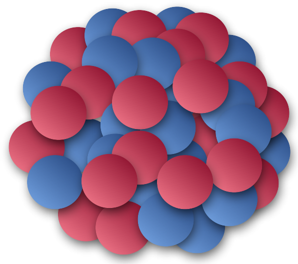
Chiral Effective Field Theory



Nuclei & nuclear matter

"Ab initio" nuclear theory

nucleons — degrees of freedom



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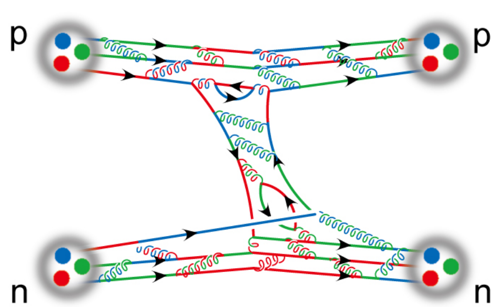

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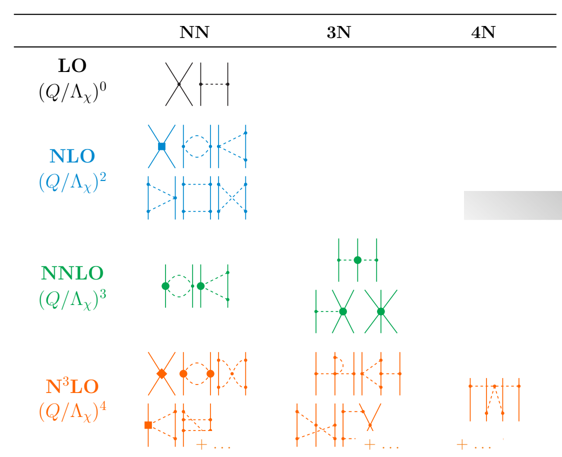
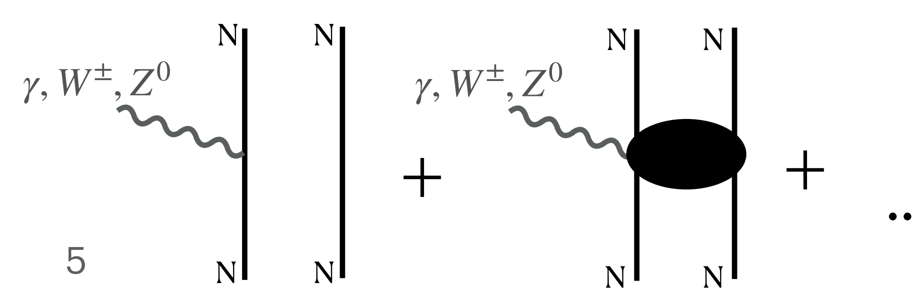


Nuclei & nuclear matter

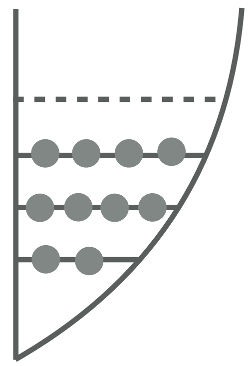
Allows to construct **electroweak currents** consistently with the chiral potential

$$j = \sum_{i=1}^{A} j_i + \sum_{j<i=1}^{A} j_{ij} + \sum_{k<j<i=1}^{A} j_{ijk} + \ldots$$



Coupled cluster theory

Reference state (Hartree-Fock): $|\Psi\rangle = a_i^\dagger a_j^\dagger \ldots a_k^\dagger |0\rangle$



Include **correlations** through e^T operator

$$\mathscr{H}_N e^T |\Psi\rangle = E e^T |\Psi\rangle$$

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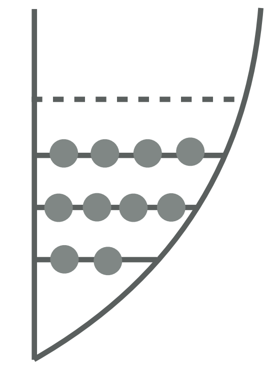


Include **correlations** through e^T operator

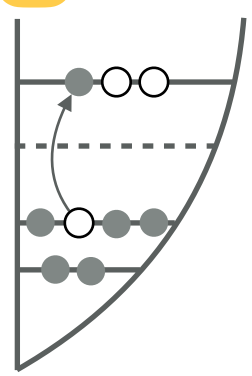
$$\mathscr{H}_N e^T |\Psi\rangle = E e^T |\Psi\rangle$$

1p1h

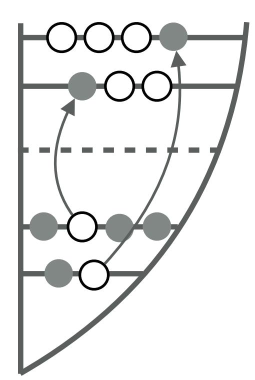
2p2h

Expansion: $T = \sum t_a^i a_a^\dagger a_i + \frac{1}{4} \sum t_{ab}^{ij} a_a^\dagger a_b^\dagger a_i a_j + \ldots$

singles



doubles



G. Hagen, T. Papenbrock, M. Hjorth-Jensen, D. J. Dean, Rep. Prog. Phys. 77, 096302 (2014).

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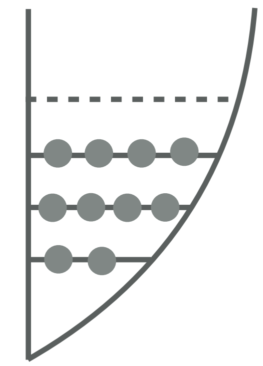

Include **correlations** through e^T operator

$$\mathscr{H}_N e^T |\Psi\rangle = E e^T |\Psi\rangle$$

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

1p1h   2p2h

$$\text{Expansion: } T = \sum t_a^i a_a^\dagger a_i + \frac{1}{4} \sum t_{ab}^{ij} a_a^\dagger a_b^\dagger a_i a_j + \ldots$$

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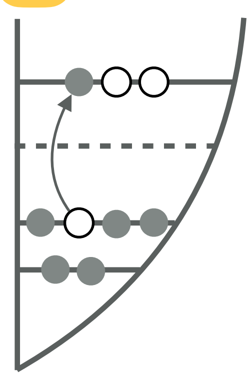

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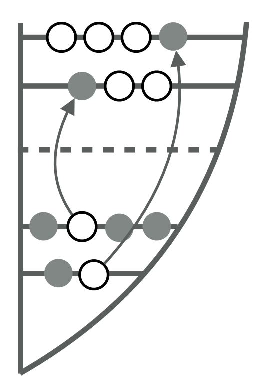

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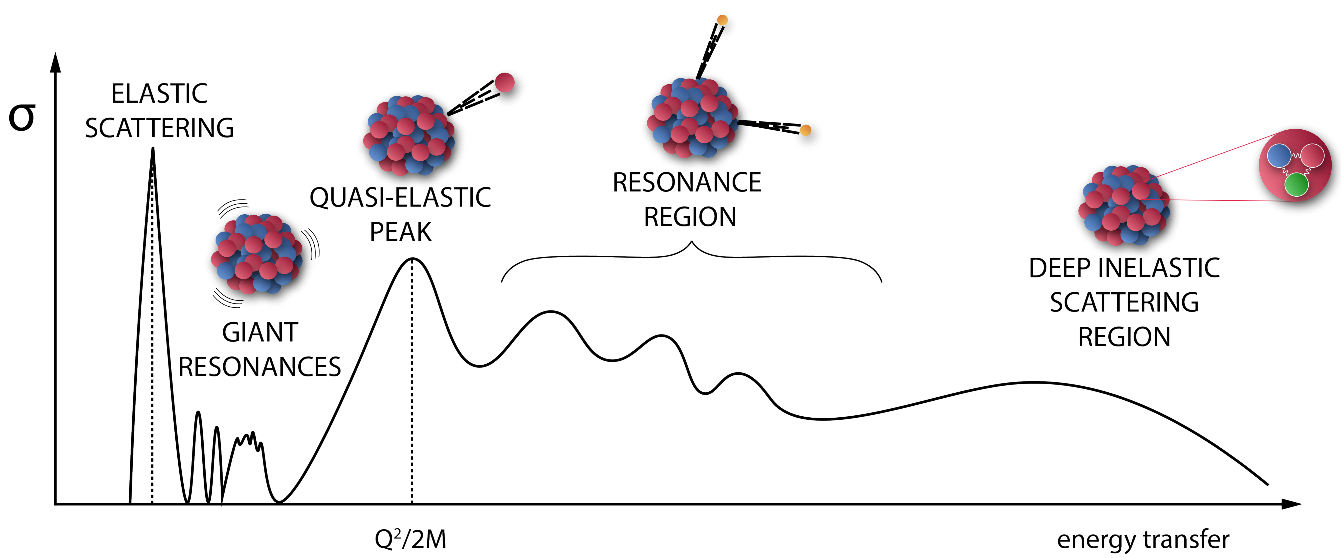
Nuclear responses

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



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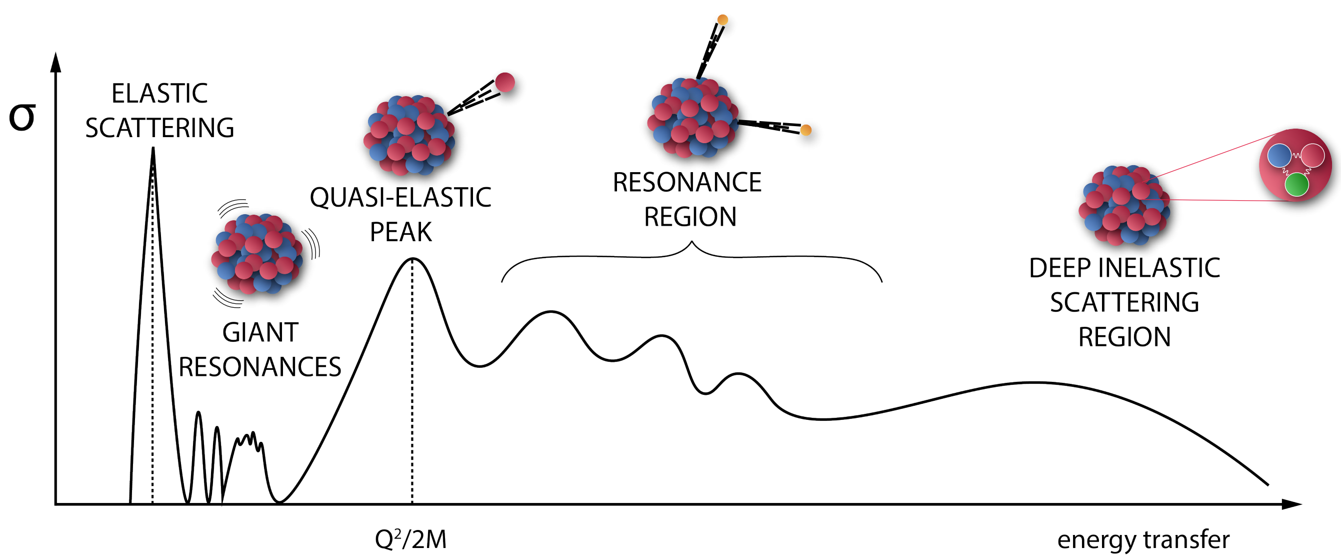
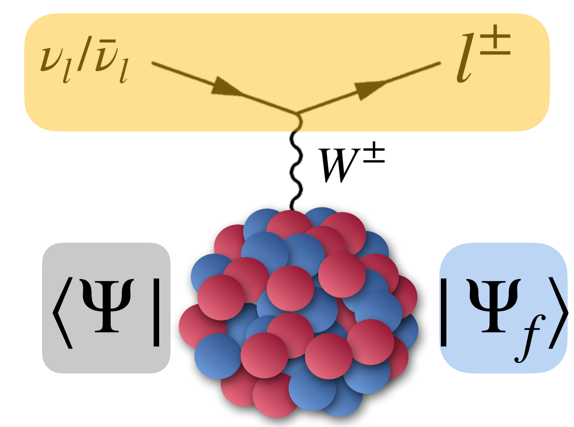


lepton tensor

nuclear responses



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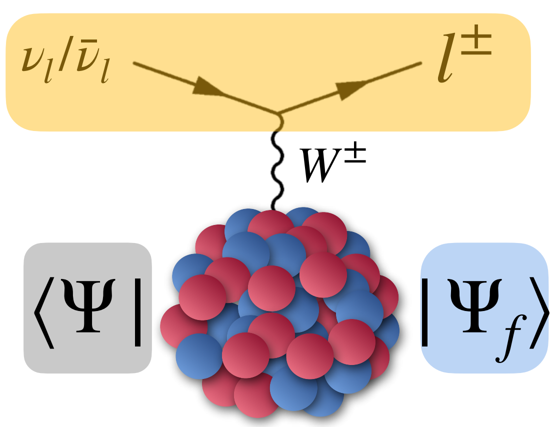
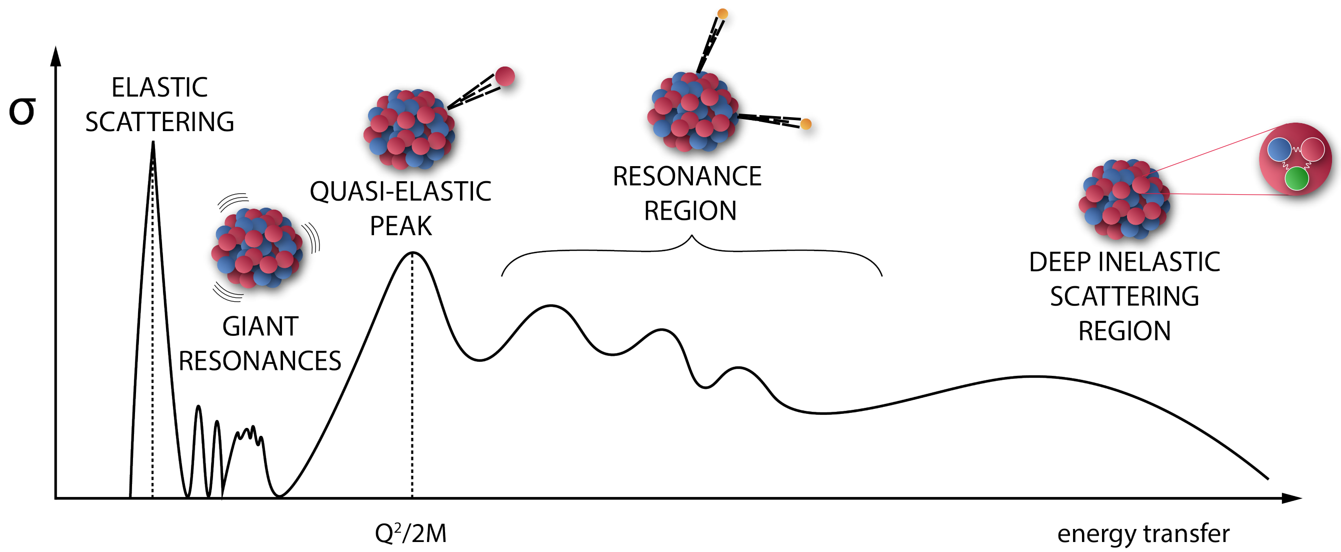




$$R_{\mu\nu}(\omega, q) = \sum_f \langle \Psi | J_\mu^\dagger(q) | \Psi_f \rangle \langle \Psi_f | J_\nu(q) | \Psi \rangle \delta(E_0 + \omega - E_f)$$

Challenging sum over continuum spectrum

Electrons for neutrinos

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

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

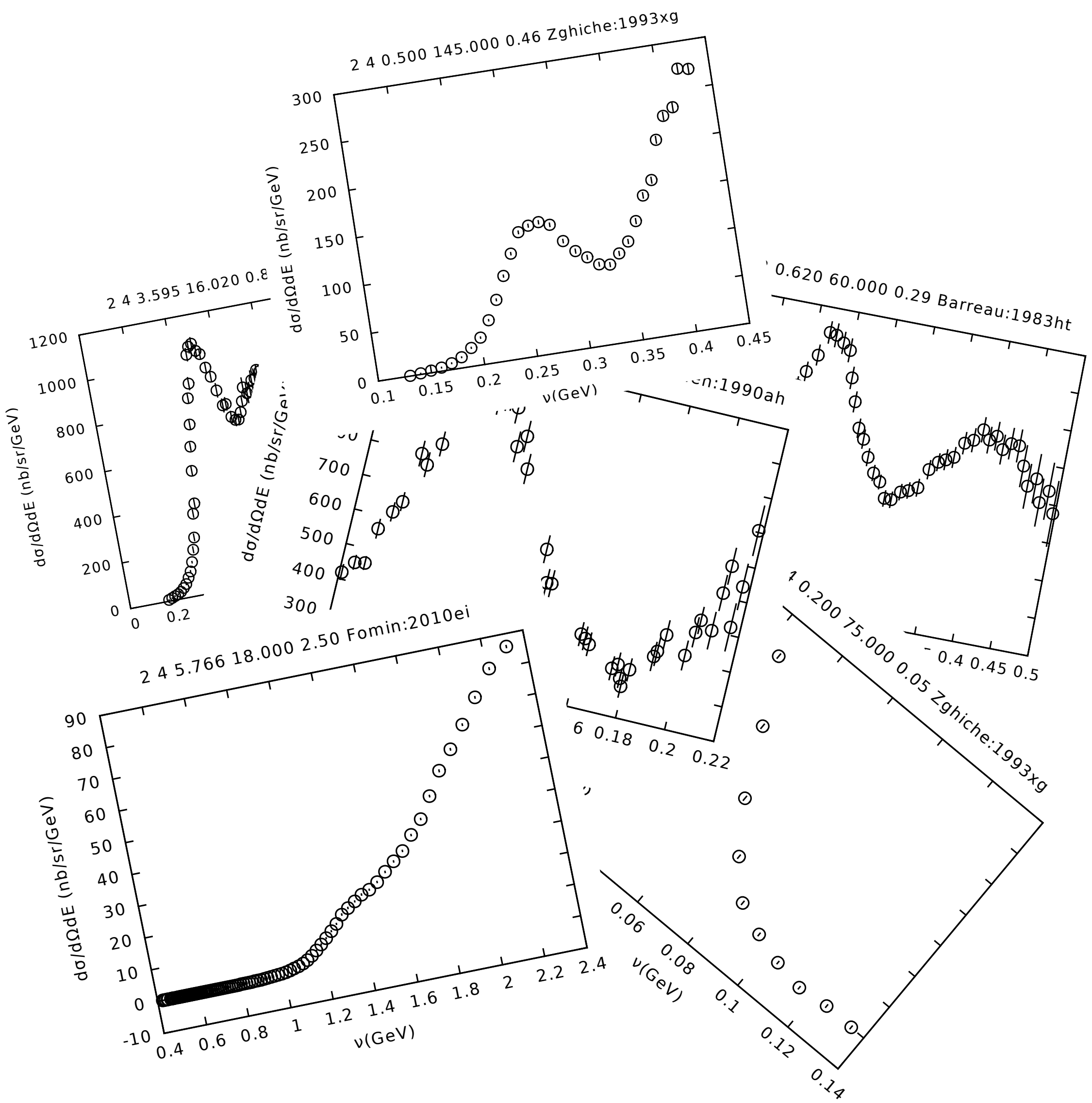
✓ much more precise data

✓ 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



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

Electron scattering: Rosenbluth separation

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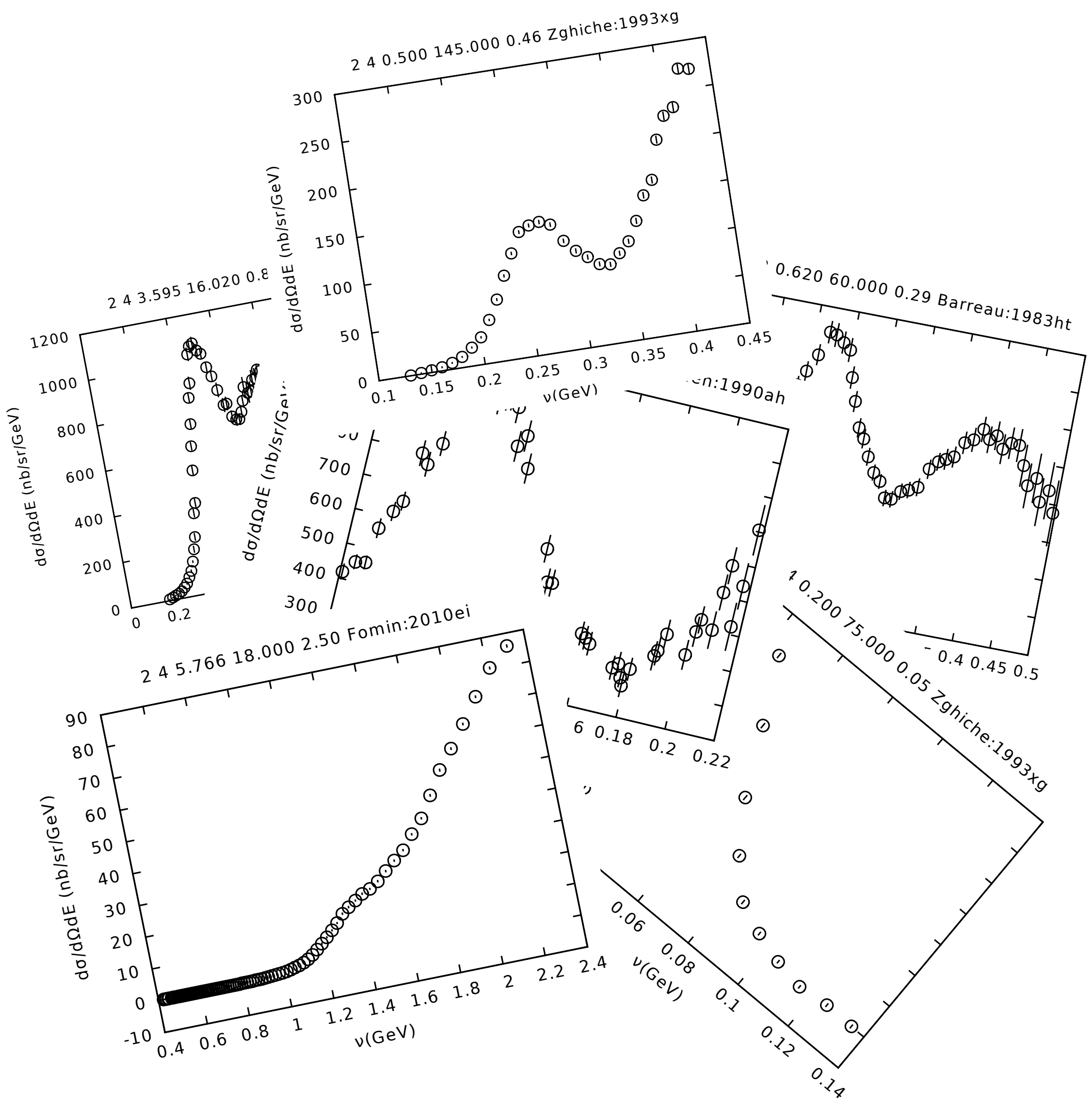

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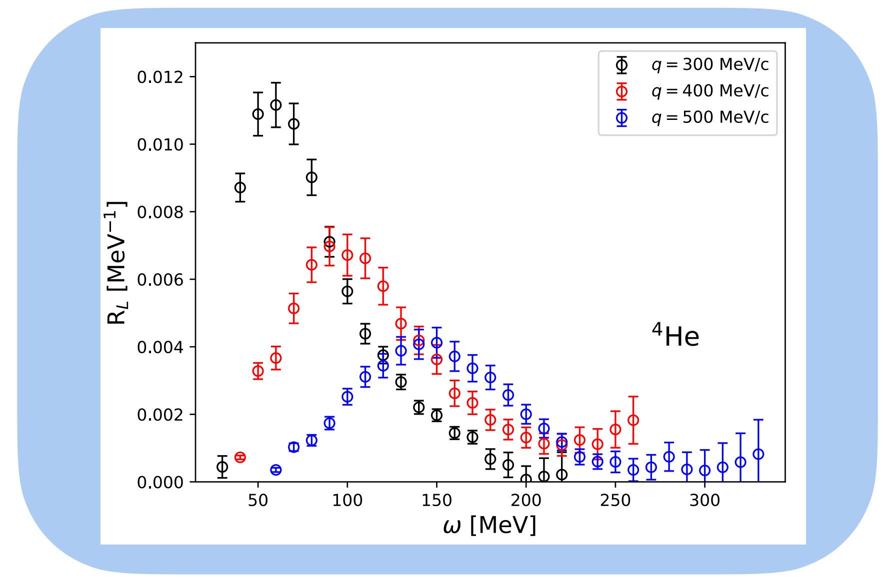
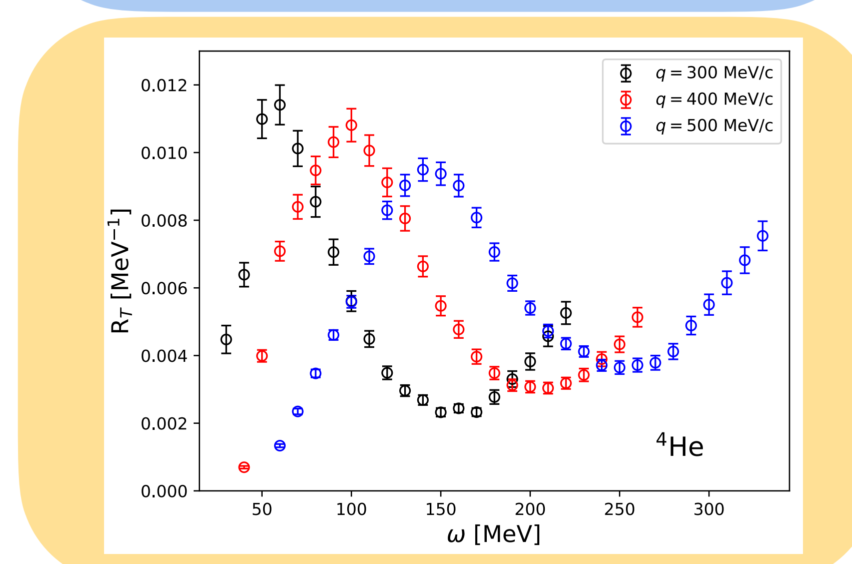
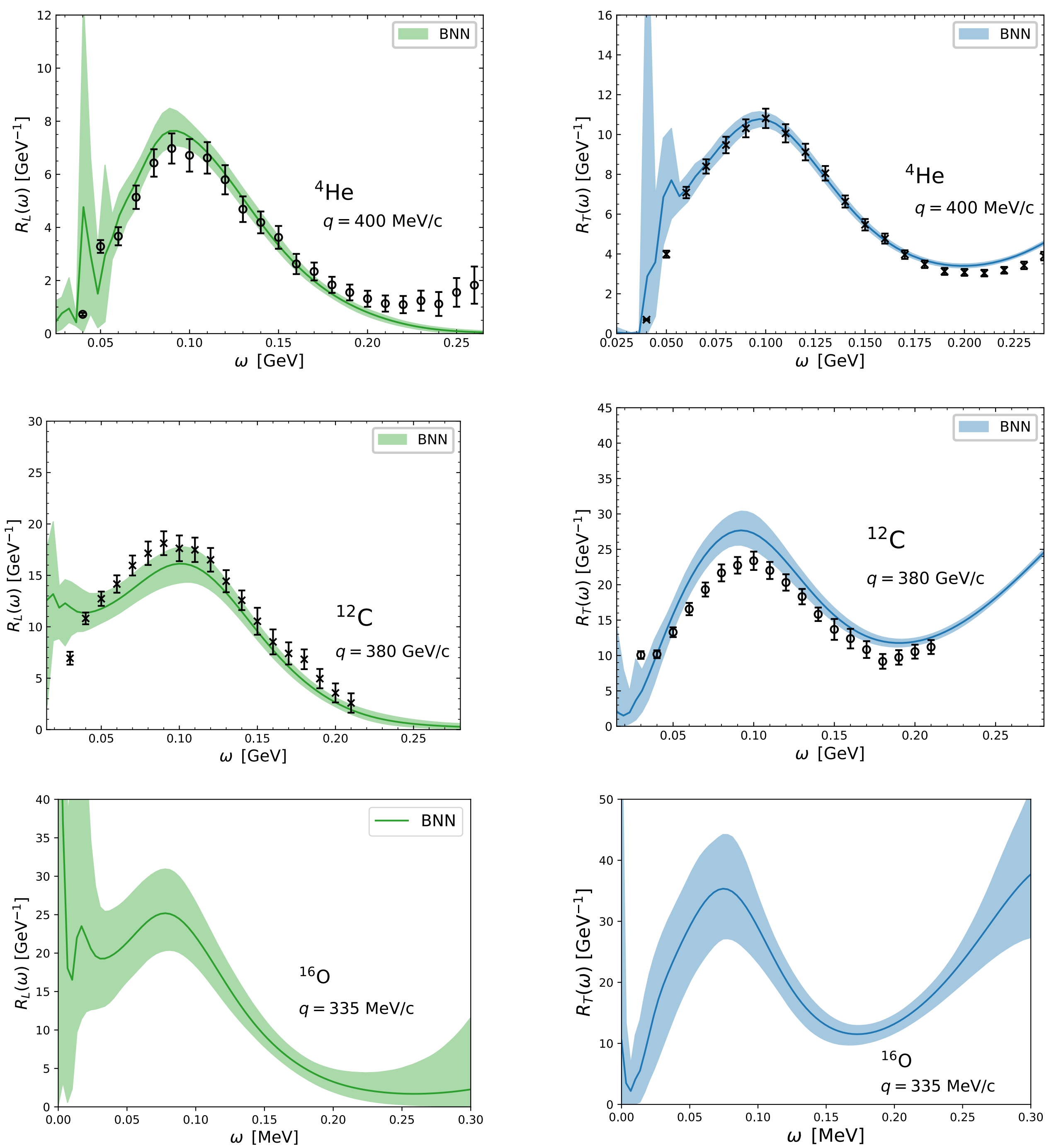




$$\left.\frac{d\sigma}{dE'd\Omega}\right|_e = \sigma_M\Big(v_L R_L(\omega,\bar{q}) + v_T R_T(\omega,\bar{q})\Big)$$

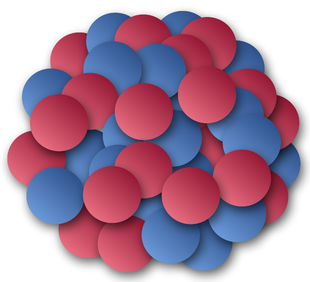
Rosenbluth separation with Bayesian neural network



- 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**

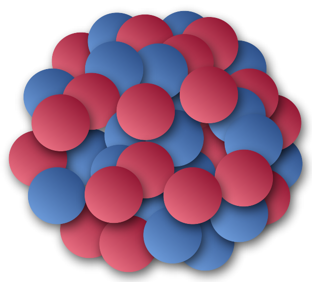
Low/high energies



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

Many-body problem

Low/high energies



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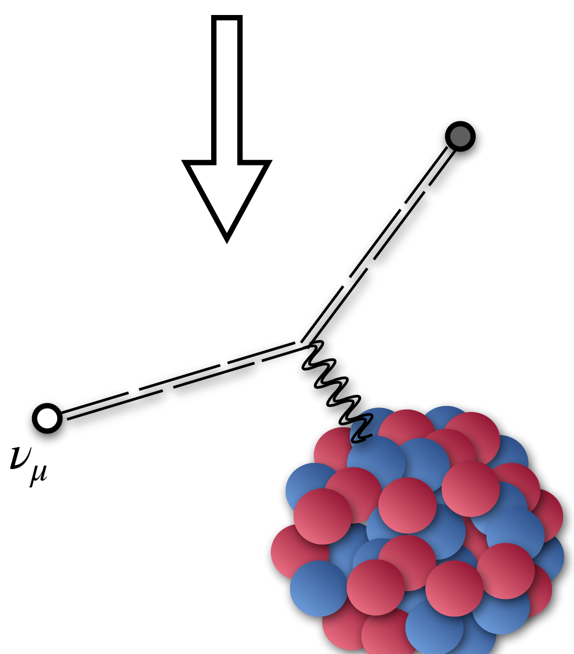
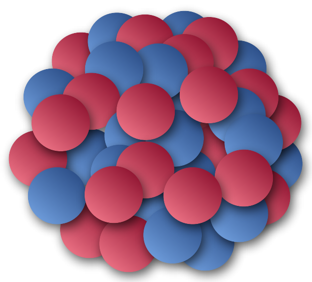


$$\langle\psi_f|\,\hat{j}\,|\psi_A\rangle$$

Electroweak responses
consistent treatment of final states

Low/high energies



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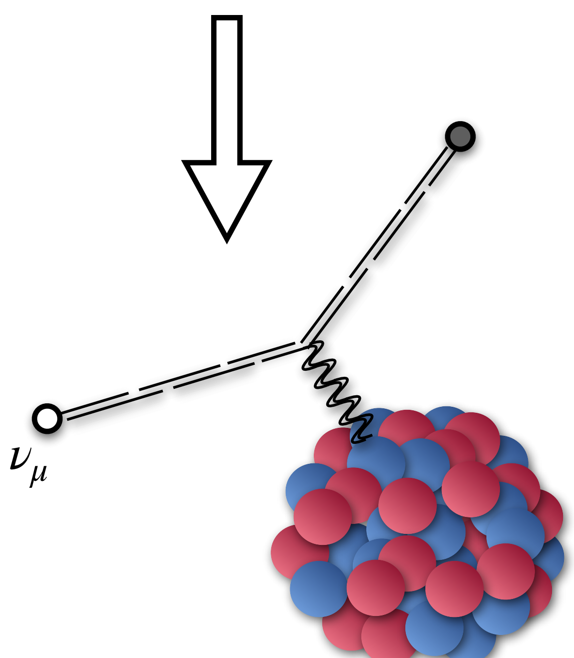

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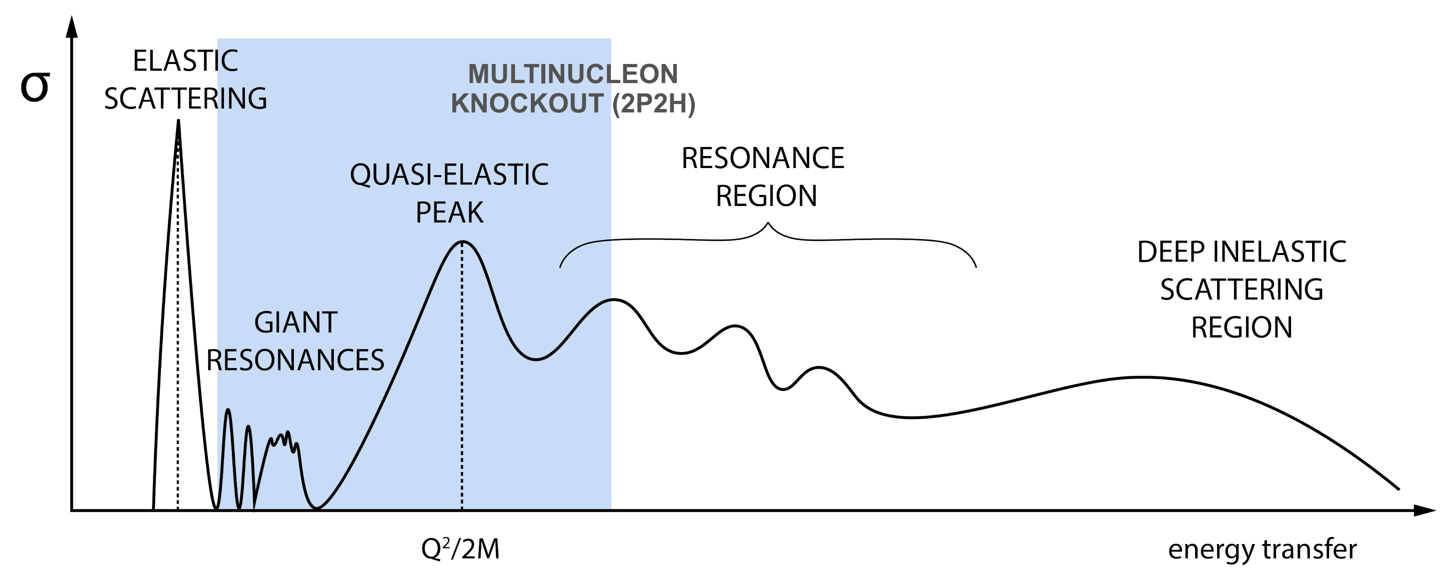

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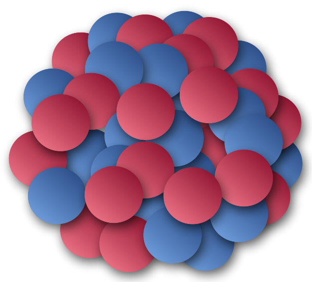

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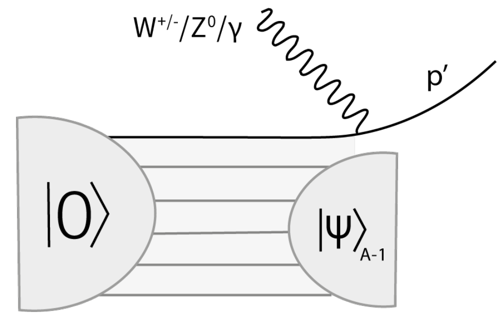
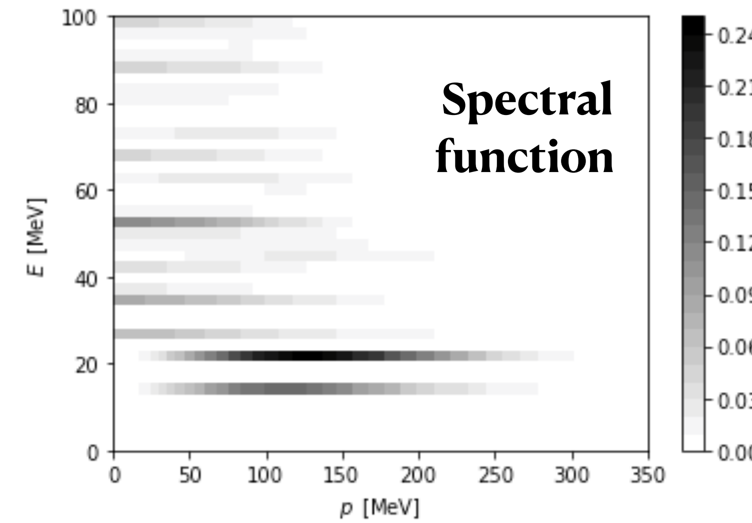
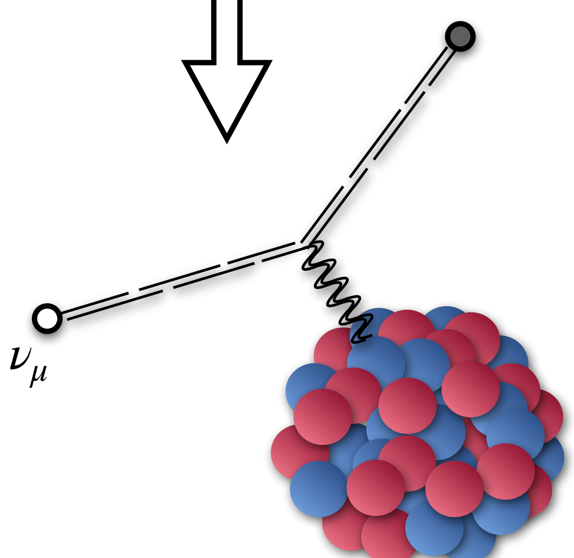


Impulse Approximation

Final state interactions neglected

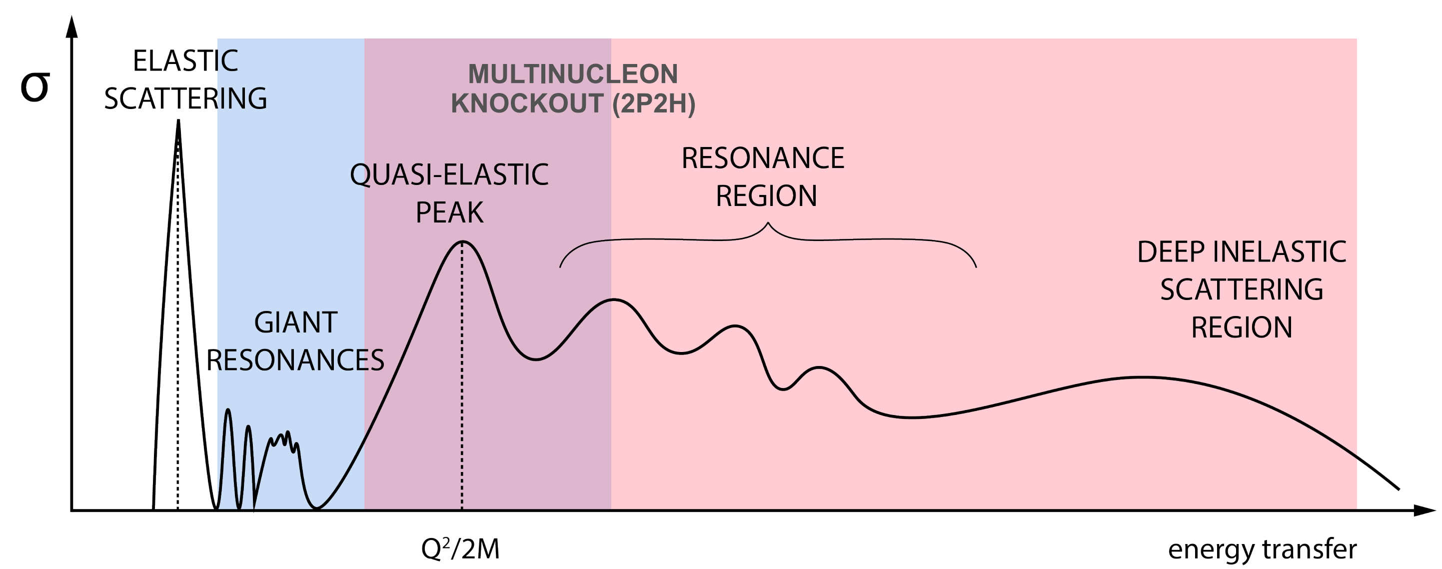


Probability density of finding nucleon $(E, \mathbf{p})$ in ground state nucleus



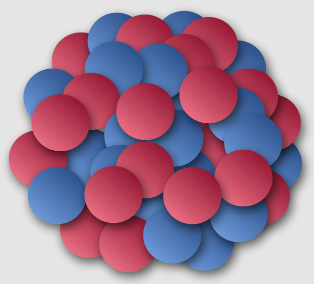
$$\langle\psi_f|\hat{j}|\psi_A\rangle$$

Electroweak responses consistent treatment of final states



HyperK & T2K scattering on ^{16}O

Low/high energies



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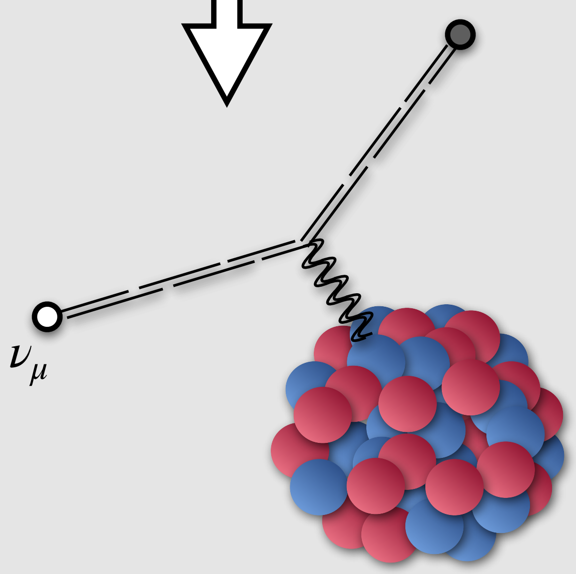
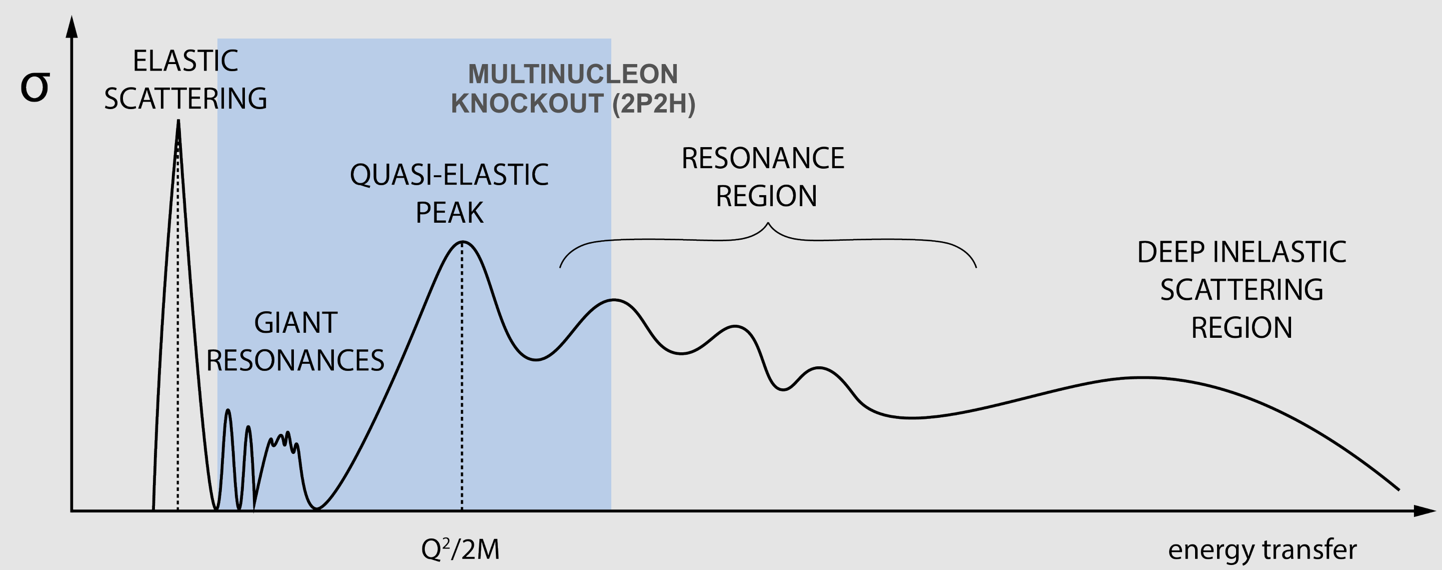
Many-body problem



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

Electroweak responses



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

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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:

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

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continuum spectrum

Integral transform

Inversion of $S_{\mu\nu}$

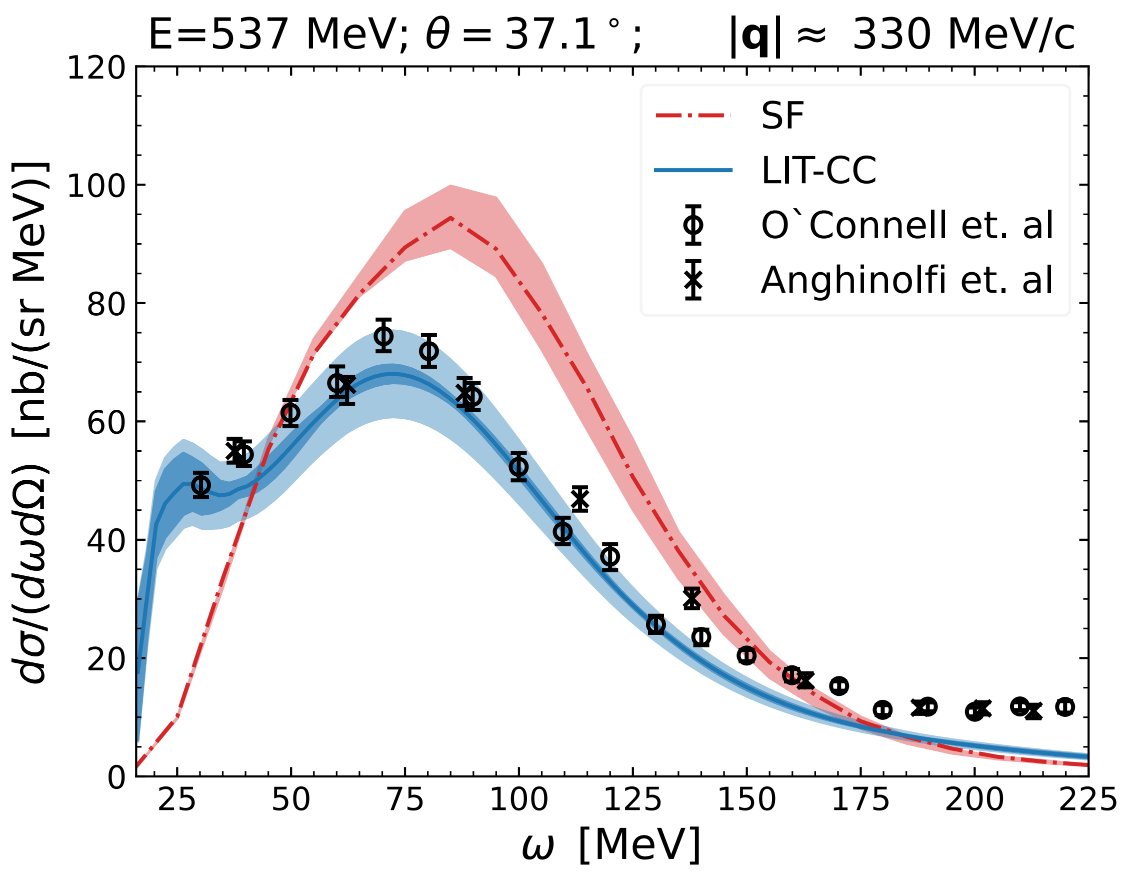
$$S_{\mu\nu}(\sigma, q) = \int d\omega K(\omega, \sigma) R_{\mu\nu}(\omega, q) = \langle \Psi | J_\mu^\dagger \, K(\mathscr{H} - E_0, \sigma) \, J_\nu | \Psi \rangle$$

Lorentzian kernel:

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

Electron scattering on ^{16}O

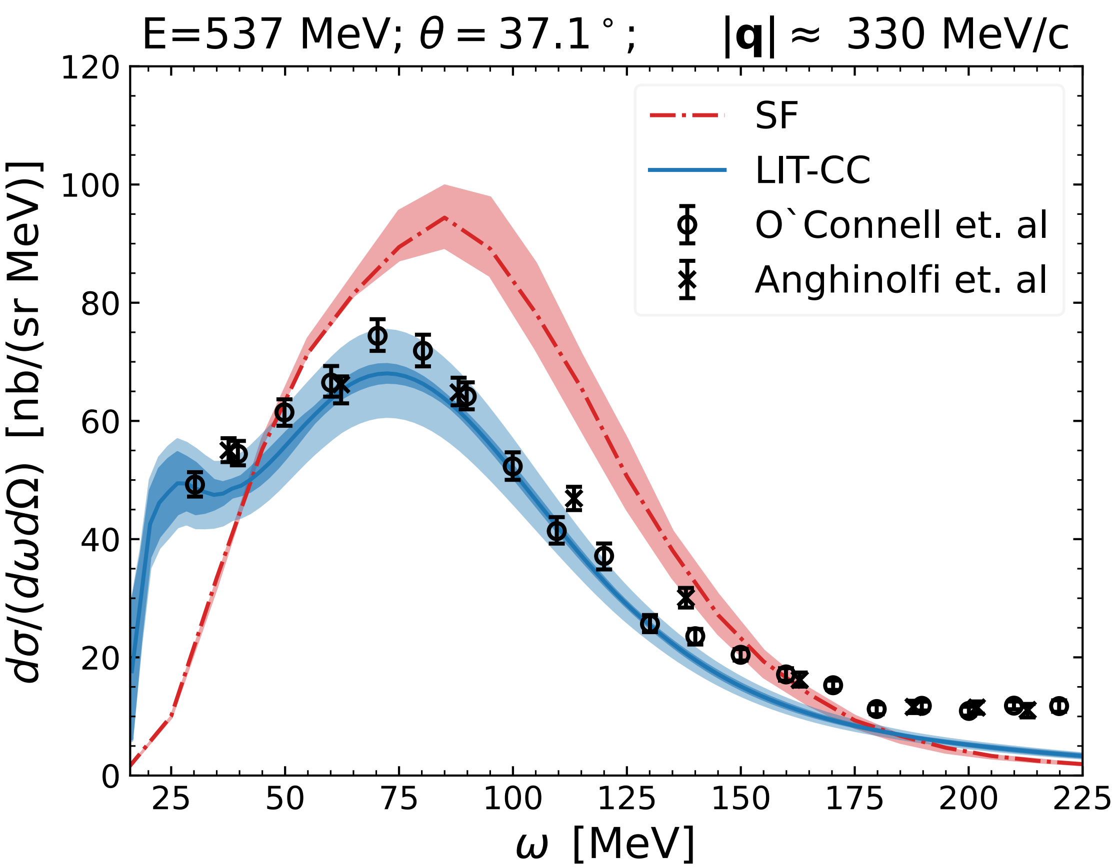
Lorentz Integral Transform + Coupled Cluster **(LIT-CC)**

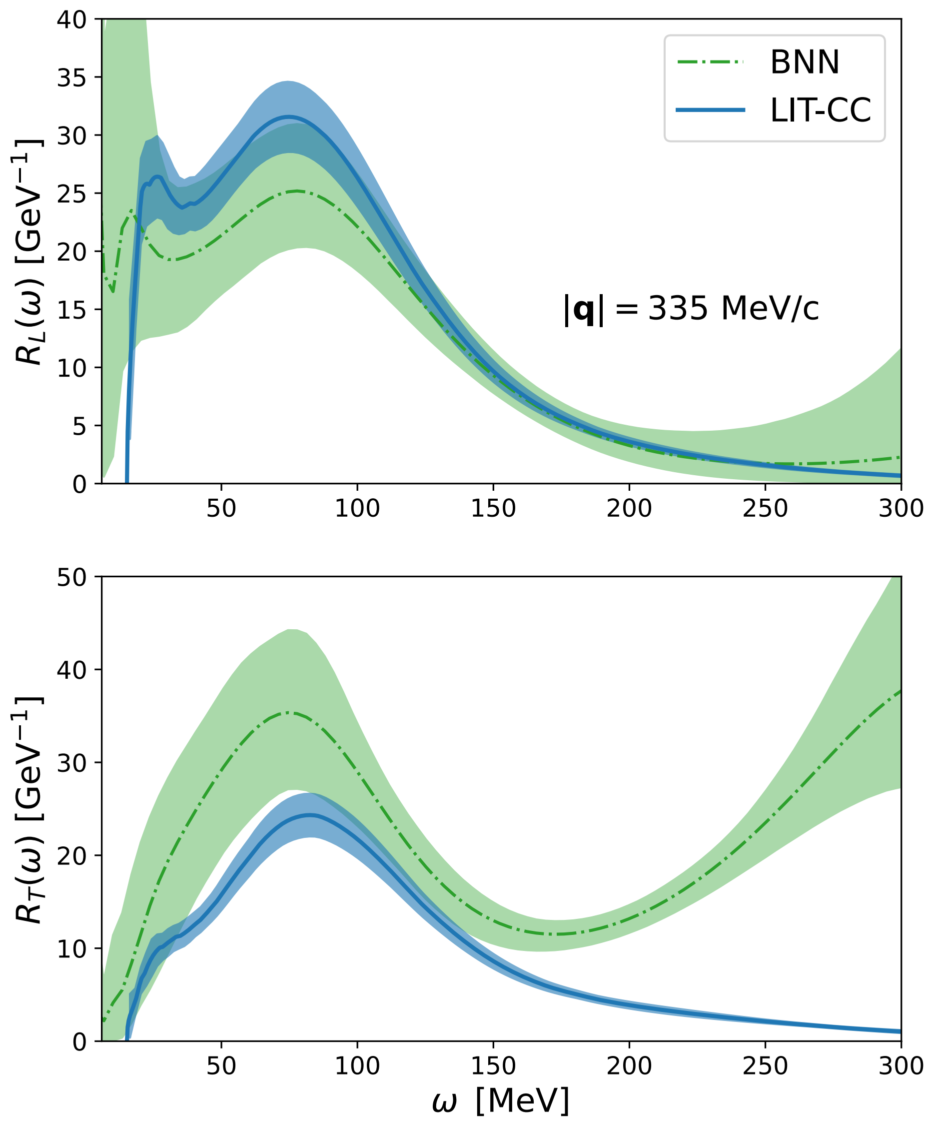


B.Acharya, JES, S. Bacca, G. Hagen W. Jiang,
***Phys. Rev. Lett.* 134.202501 (2025)**

Electron scattering on ^{16}O

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





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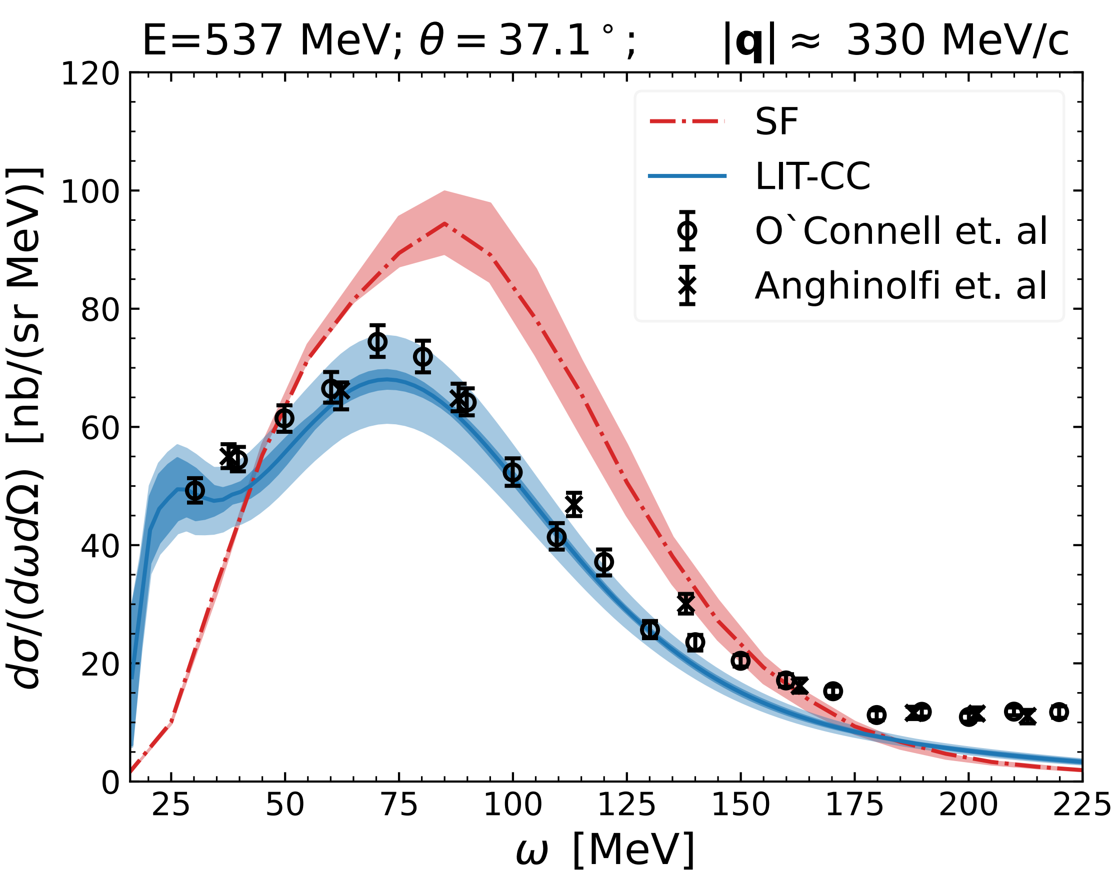
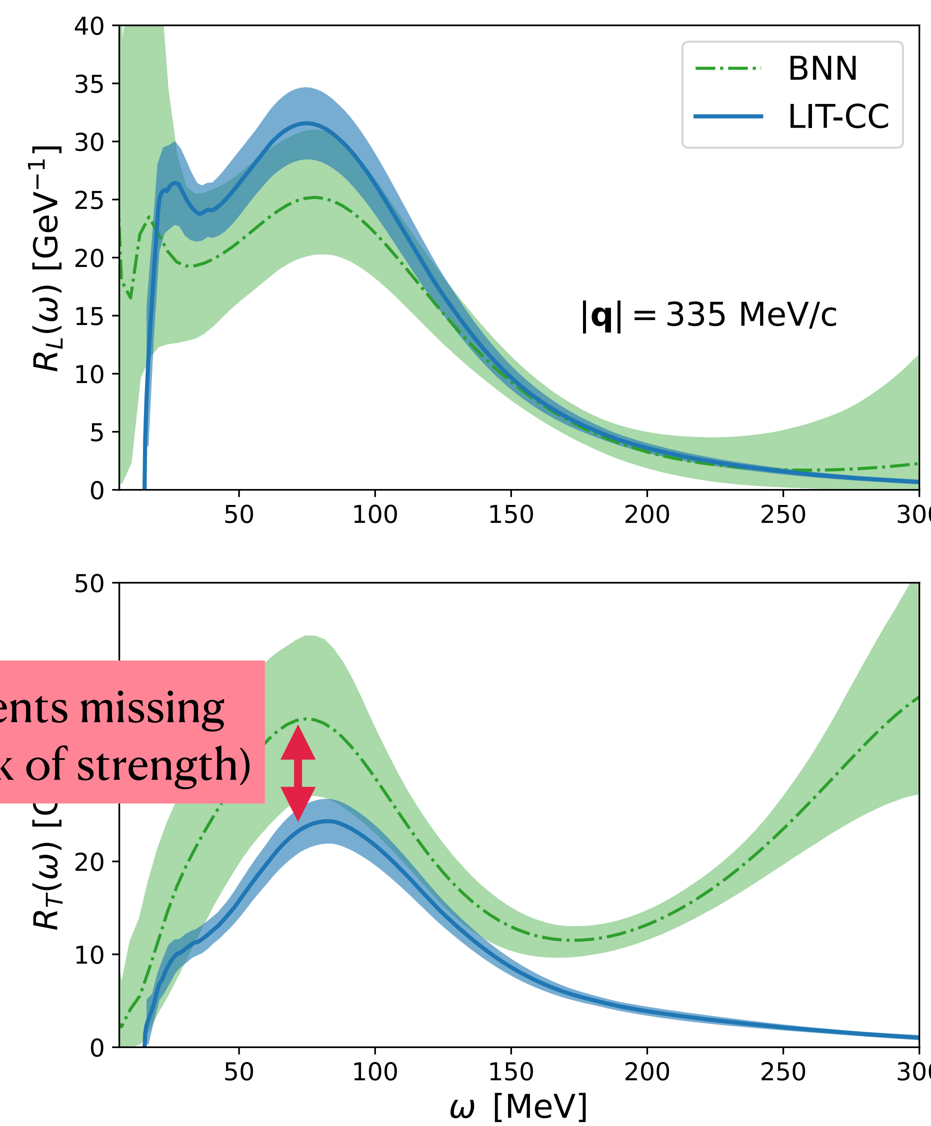




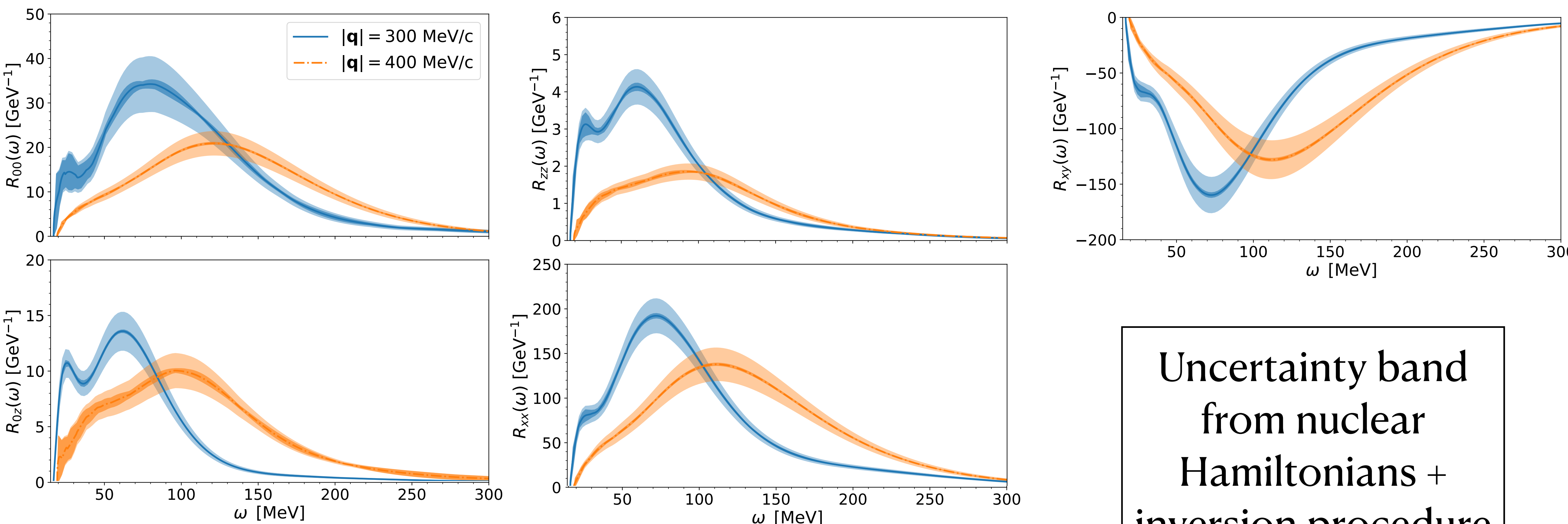
2-body currents missing
(expected lack of strength)

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

Neutrino charge-current scattering on ^{16}O

LIT-CC

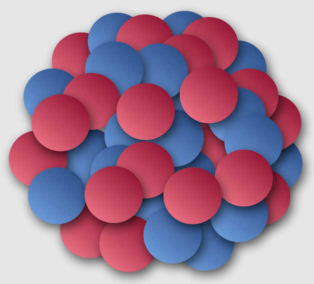
$$\left.\frac{d\sigma}{dE'd\Omega}\right|_{\nu/\bar{\nu}} = \sigma_0\Big(v_{00}R_{00} + v_{0z}R_{0z} + v_{zz}R_{zz} + v_T R_T \pm v_{xy}R_{xy}\Big)$$



Uncertainty band from nuclear Hamiltonians + inversion procedure

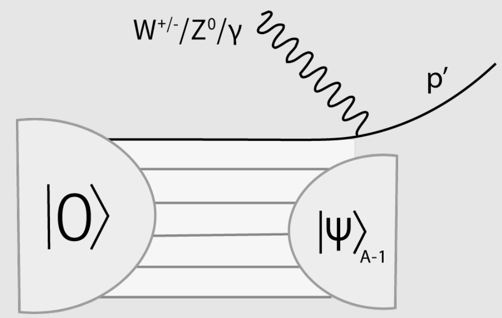
B.Acharya, JES, S. Bacca, G. Hagen W. Jiang, ***Phys. Rev. Lett.* 134.202501 (2025)**

Low/high energies

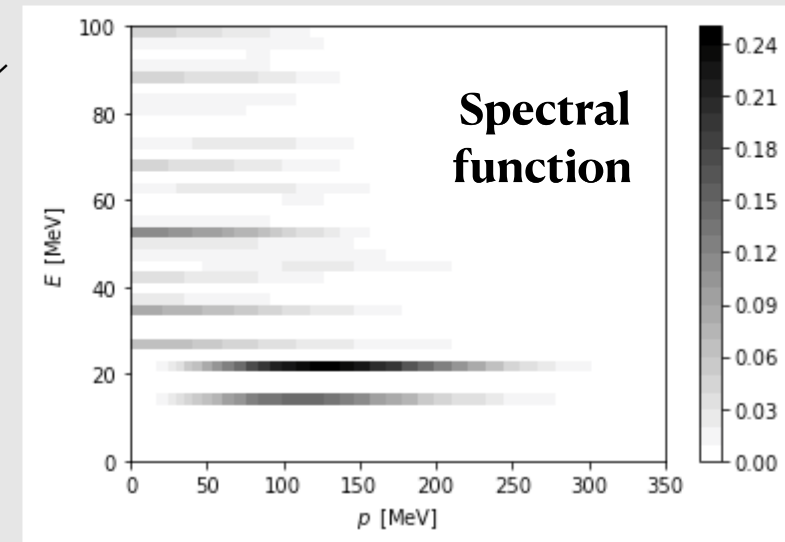


$\hat{H}|\psi_A\rangle = E|\psi_A\rangle$

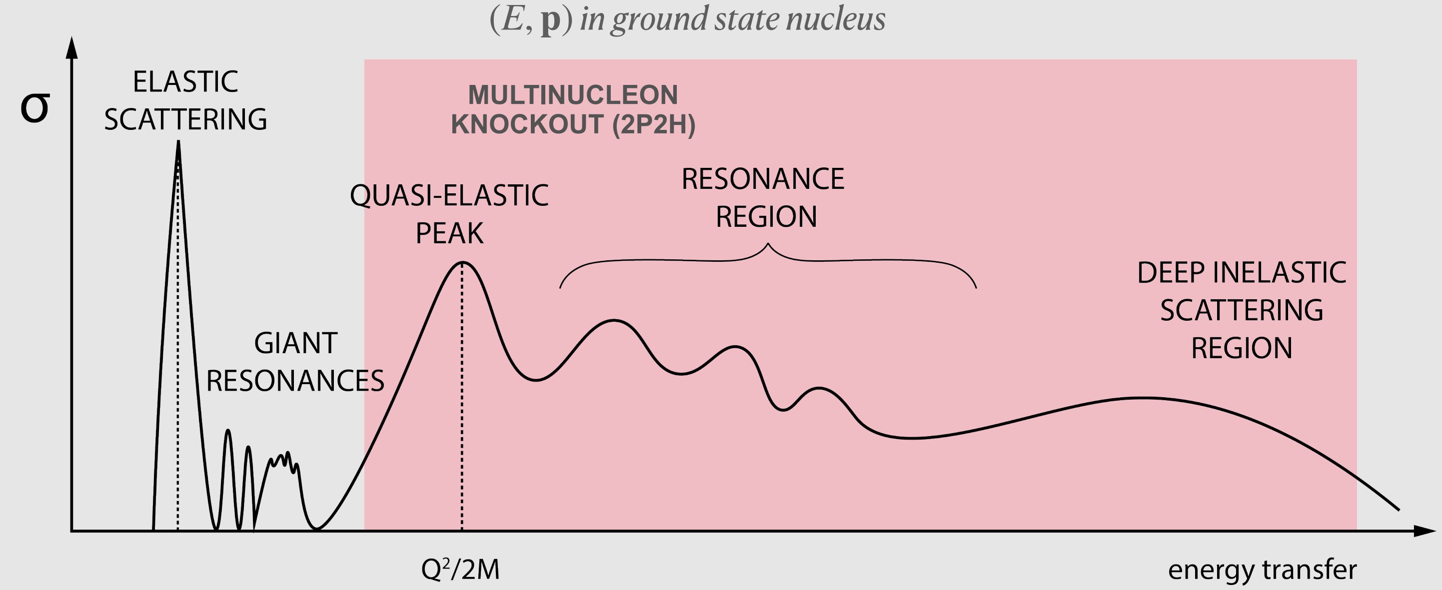
Many-body problem



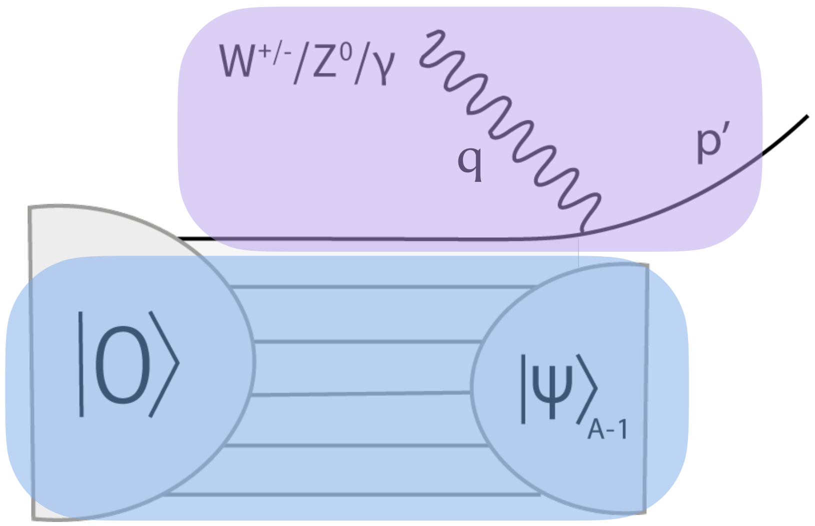
Impulse Approximation



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



^{16}O spectral function



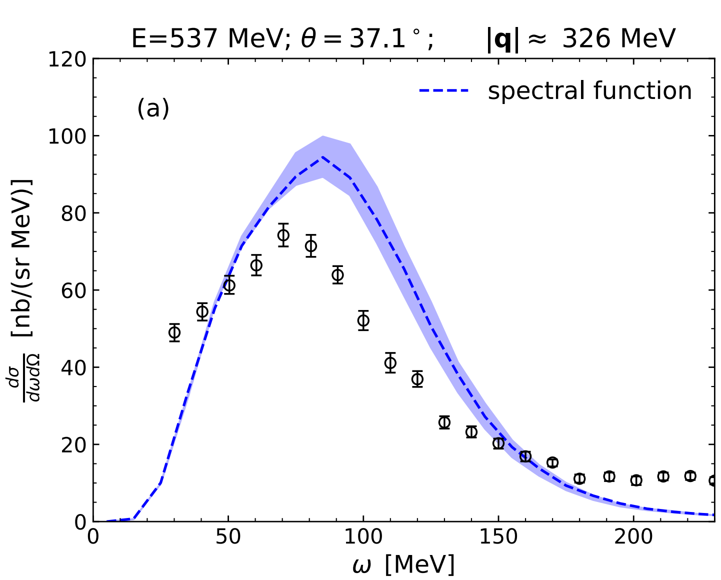
$$\sigma \propto |\mathcal{M}|^2 S(E, p)$$

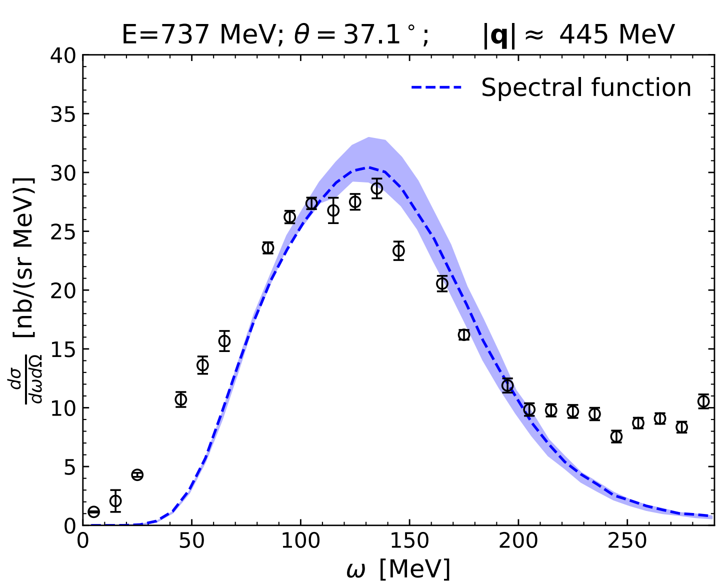
Factorized interaction vertex (relativistic, pion production...)

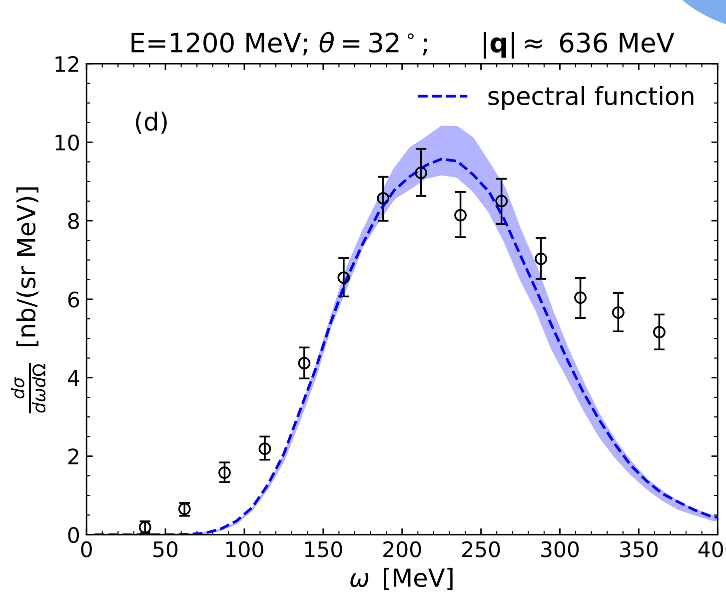
Spectral function - nuclear information

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

Scattering off ^{16}O







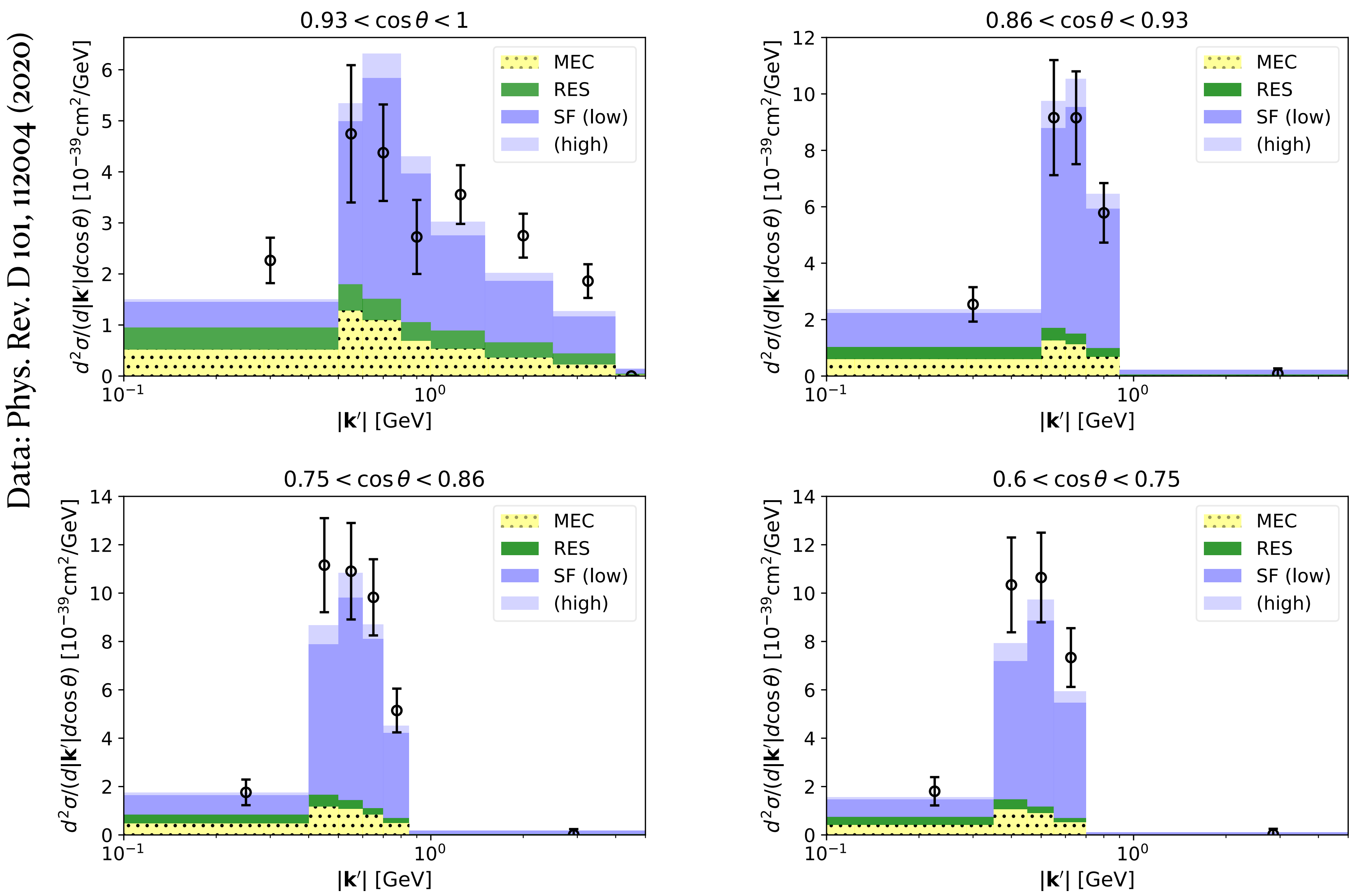
JES , S. Bacca, ***Phys. Rev. C* 109 044314**

^{16}O spectral function

Error propagation to cross sections

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

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



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

^{16}O spectral function: probing New Physics

Effective Lagrangian:

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

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

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

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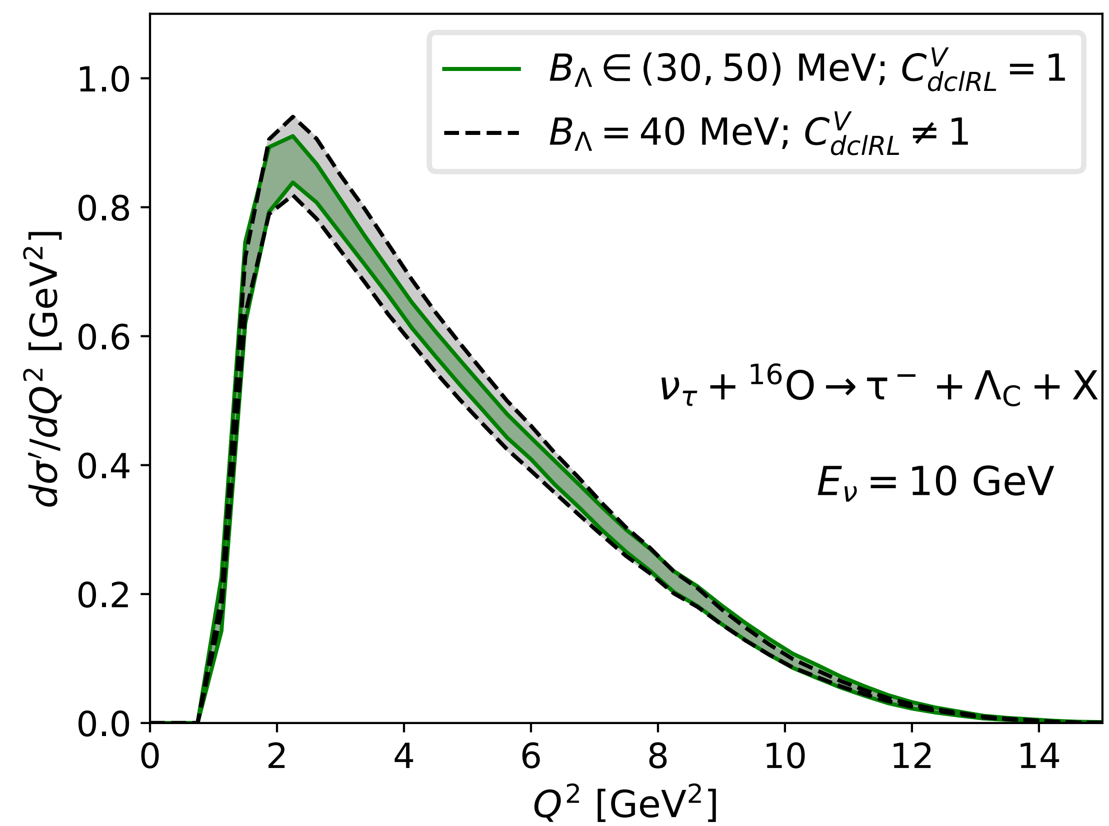
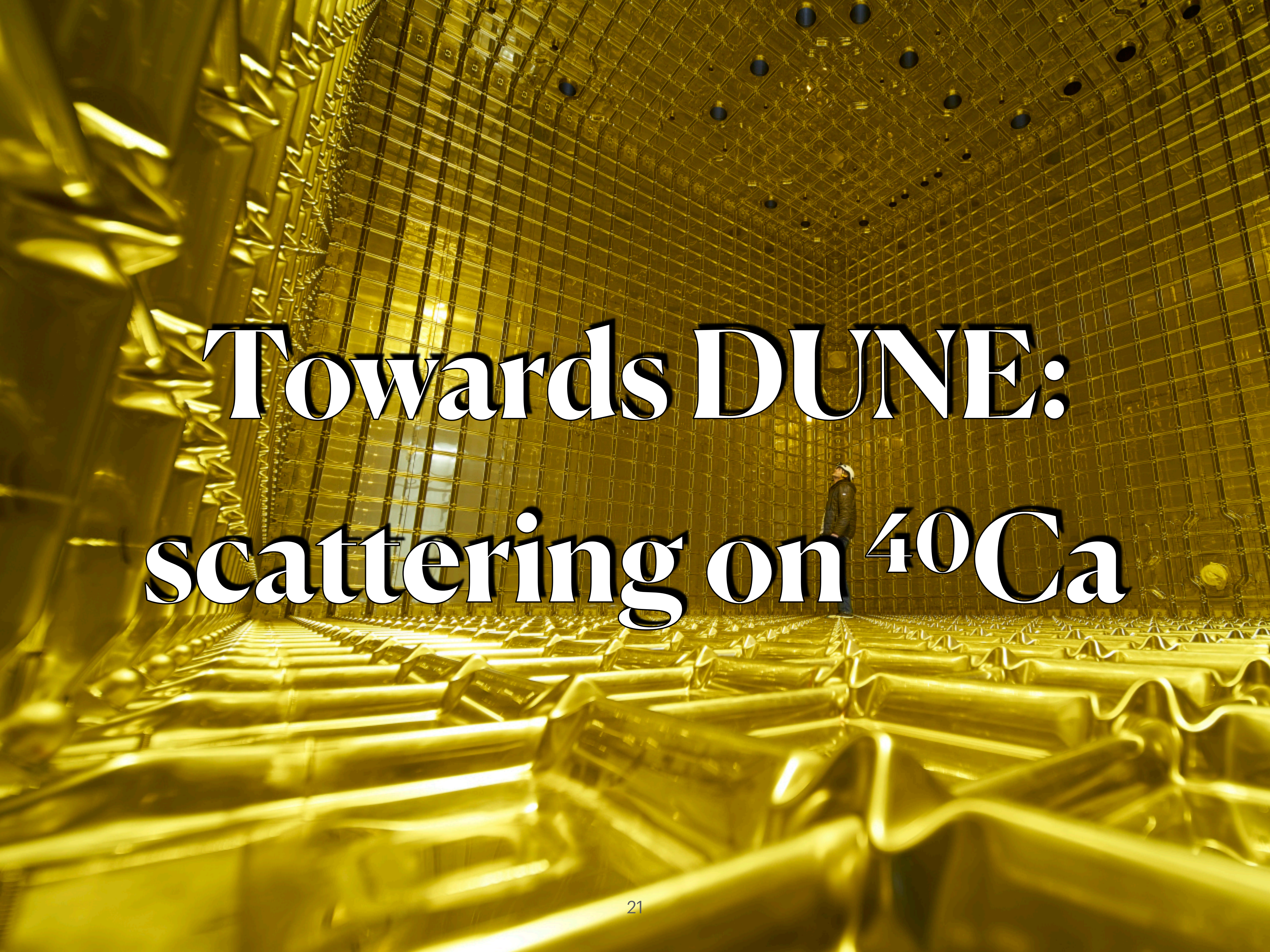
- Could we constrain them looking at $\nu_\tau n \to \tau^- \Lambda_c$?
- **NEED TO ACCOUNT FOR NUCLEAR EFFECTS:** spectral function for initial nucleon; binding energy for produced Λ_C



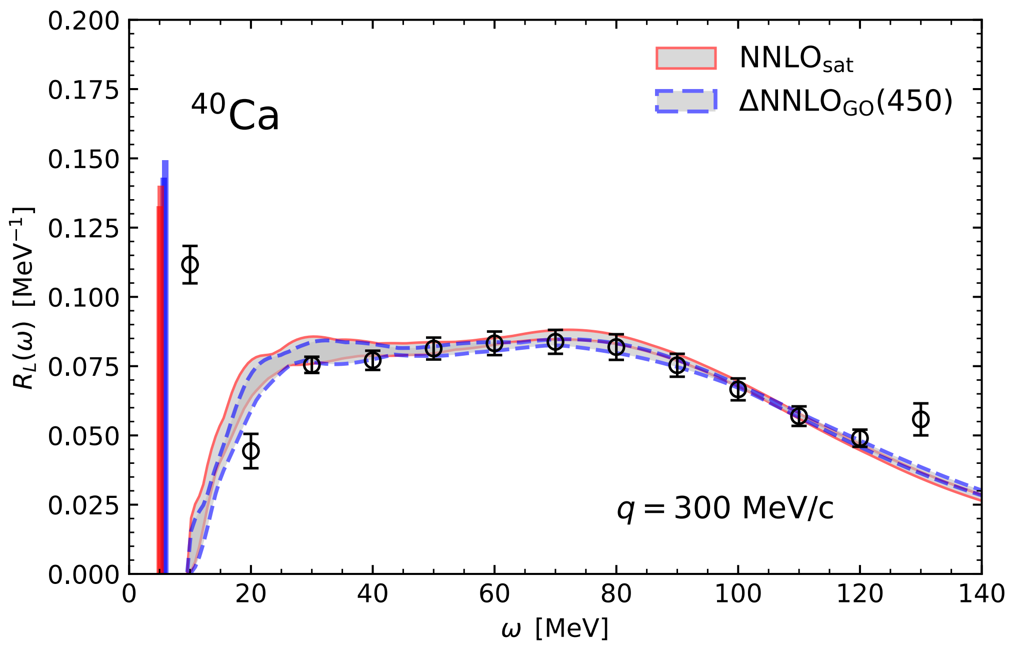
High precision of Λ_C properties in nuclear medium needed to gain sensitivity to BSM



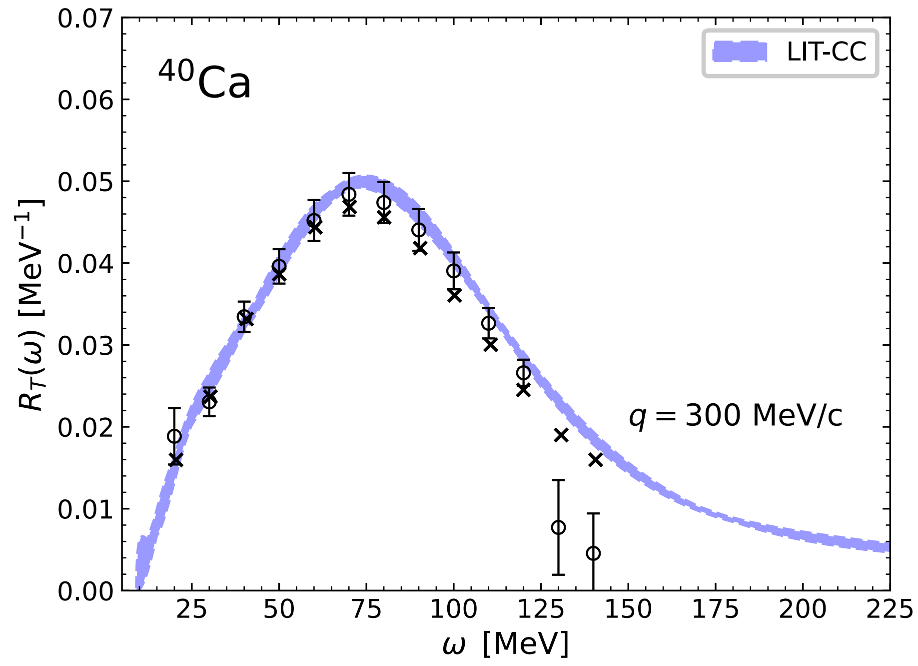
Towards DUNE: scattering on ^{40}Ca

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

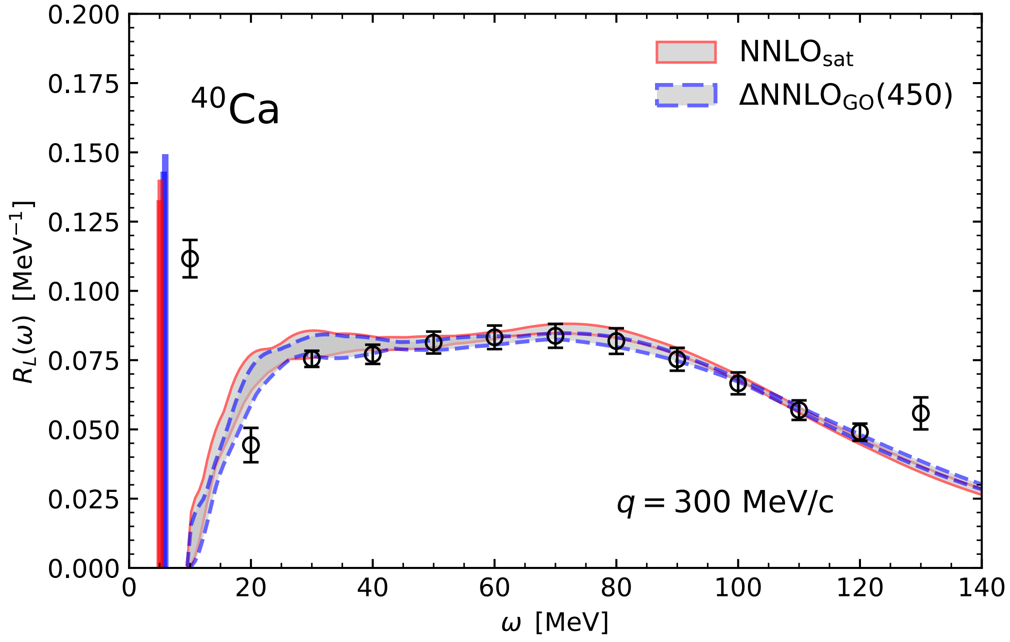
✓ Two different chiral Hamiltonians

✓ Uncertainty from LIT inversion

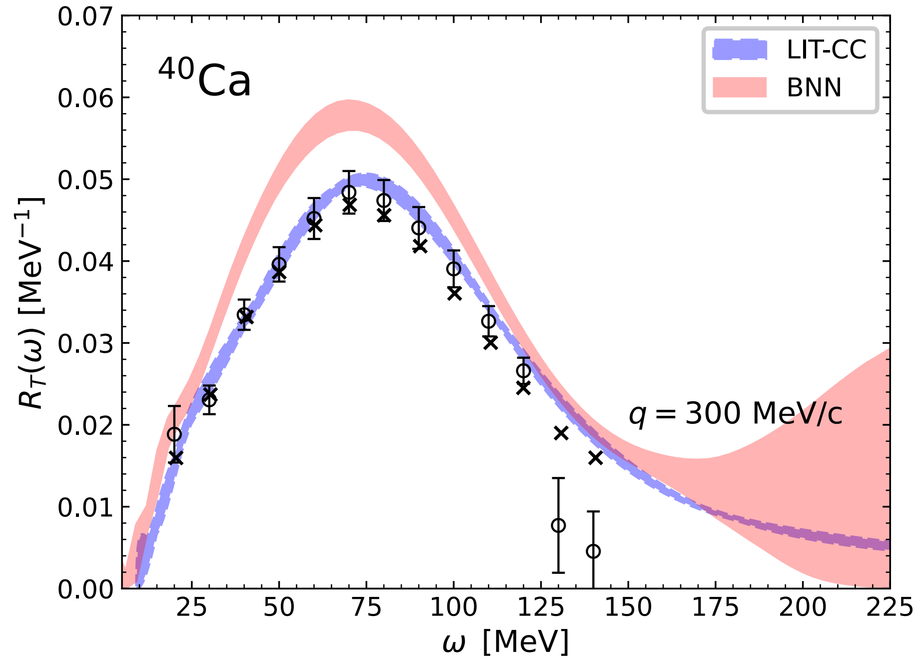
First ab-initio results for many-body system of 40 nucleons

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

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

Summary & outlook

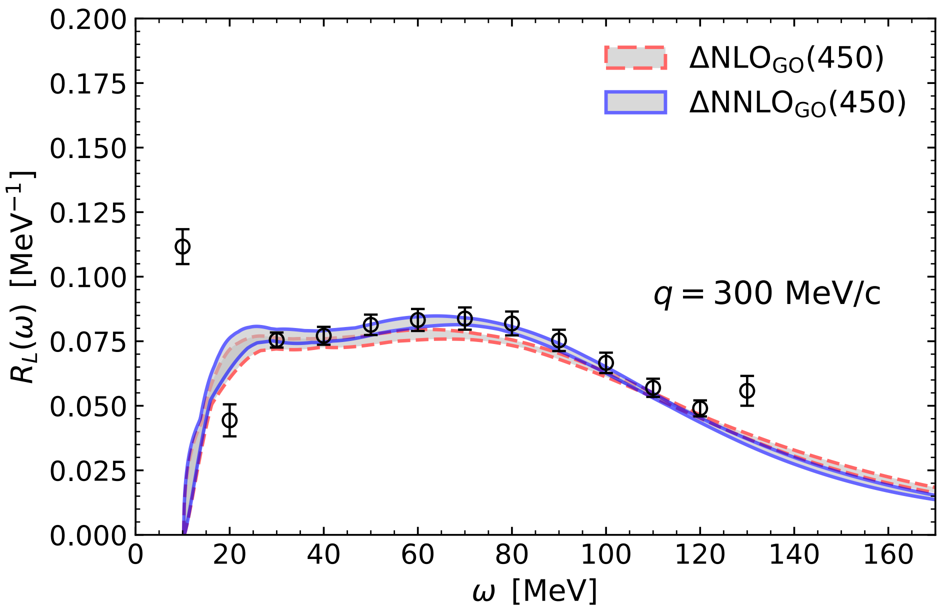
- First nuclear responses of medium-mass systems at intermediate momentum transfers
  - Uncertainty quantification from first principles
  - Path towards ^{40}Ar
  - Next step: include 2-body currents
- Spectral function formalism:
  - Interface with hadron physics (e.g. pion production)
  - Semi-exclusive cross-sections

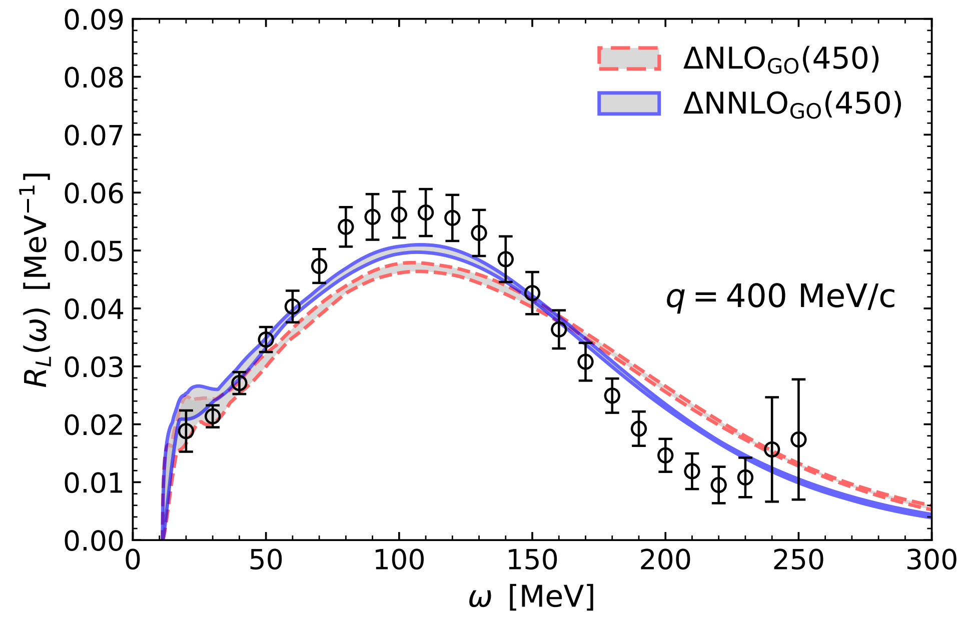
Thank you for attention!

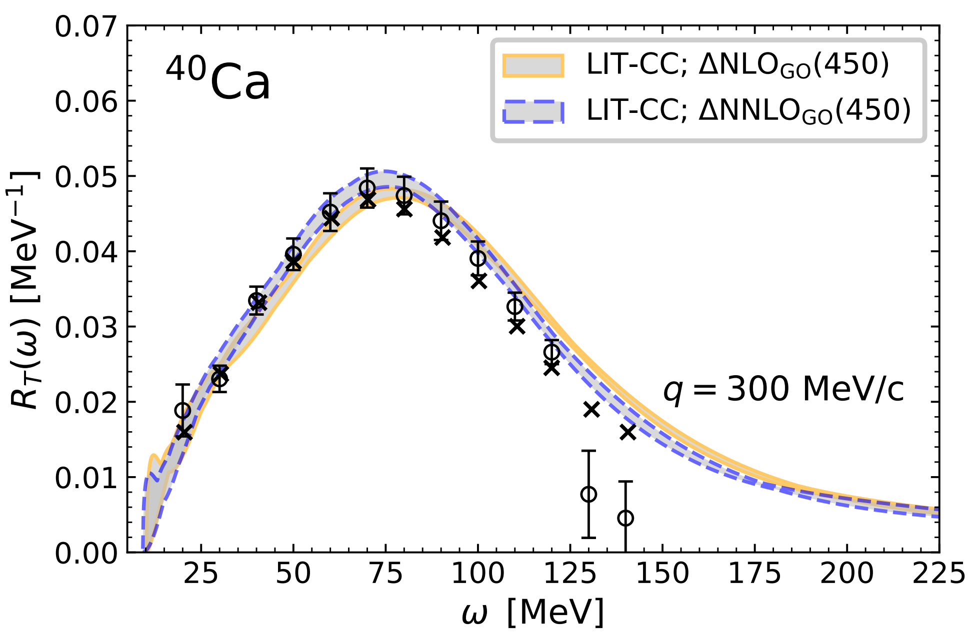
Back up

Chiral expansion for ^{40}Ca

(Electromagnetic responses)







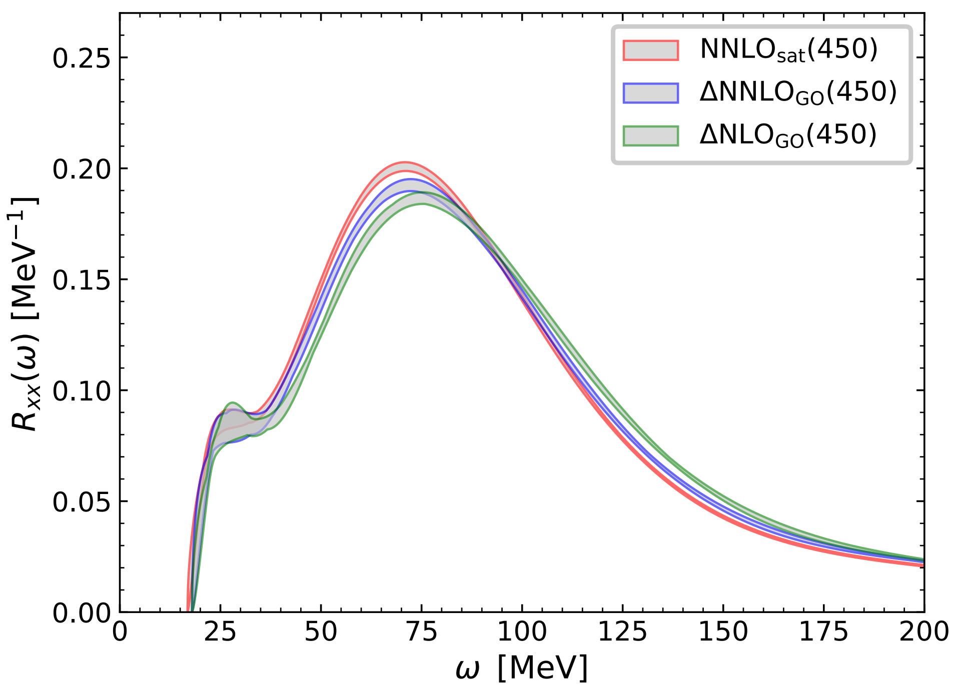
- ✓ Two orders of chiral expansion
- ✓ Convergence better for lower q (as expected)
- ✓ Higher order brings results closer to the data

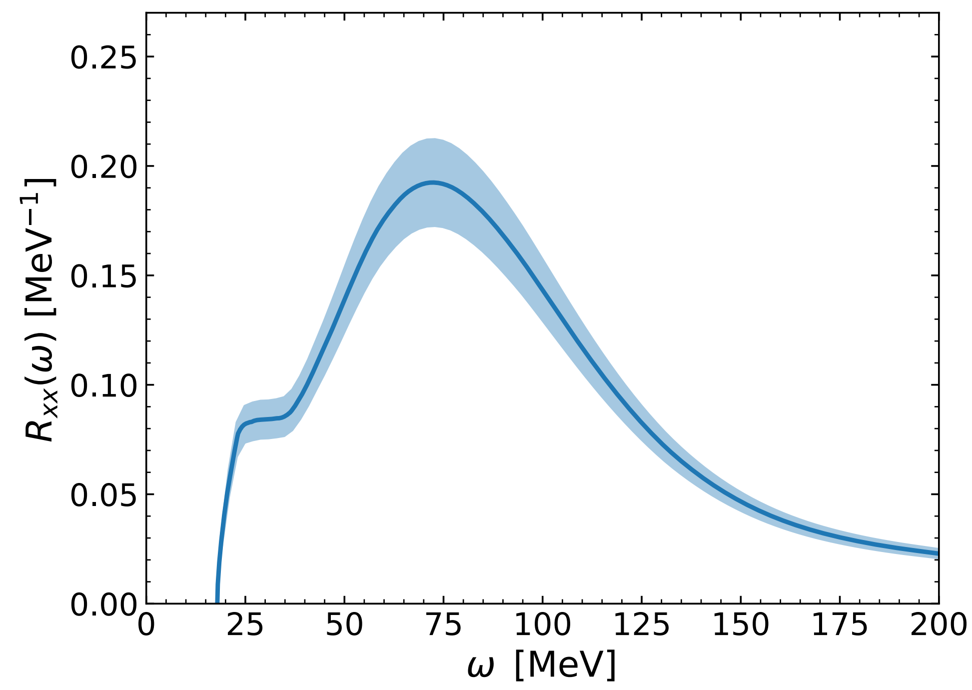
B. Acharya, S. Bacca, JES et al. Front. Phys. 1066035(2022)

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

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

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

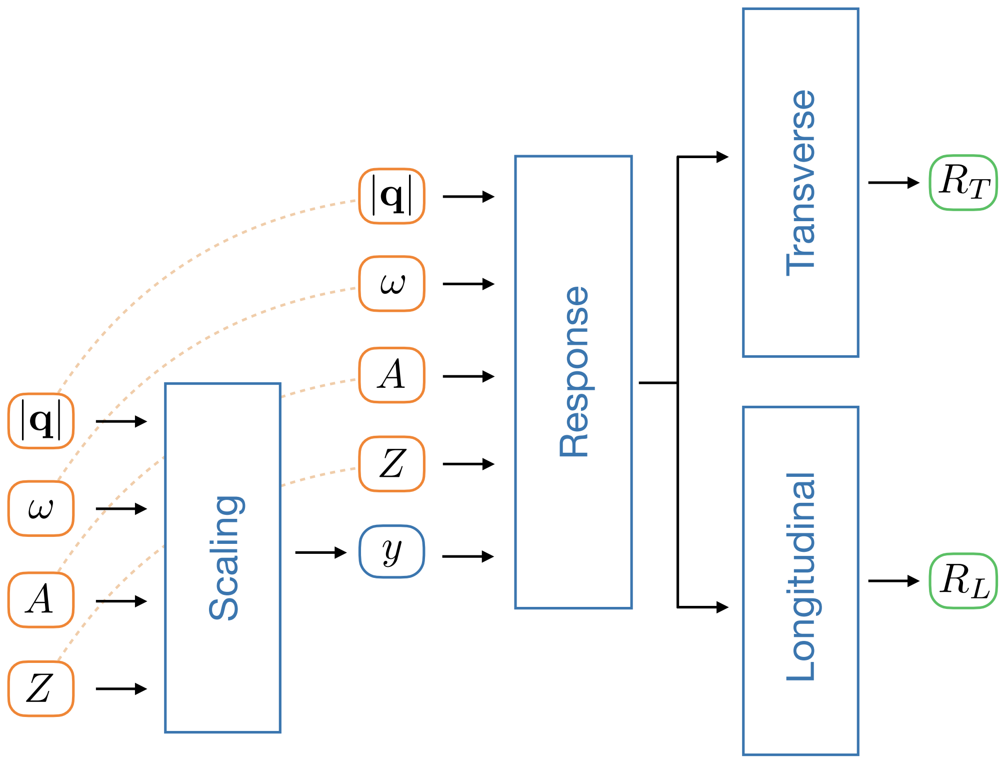
$\mathcal{W} = w_1, \ldots, w_{N_p}$ - parameters of BNN treated as probability distribution

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

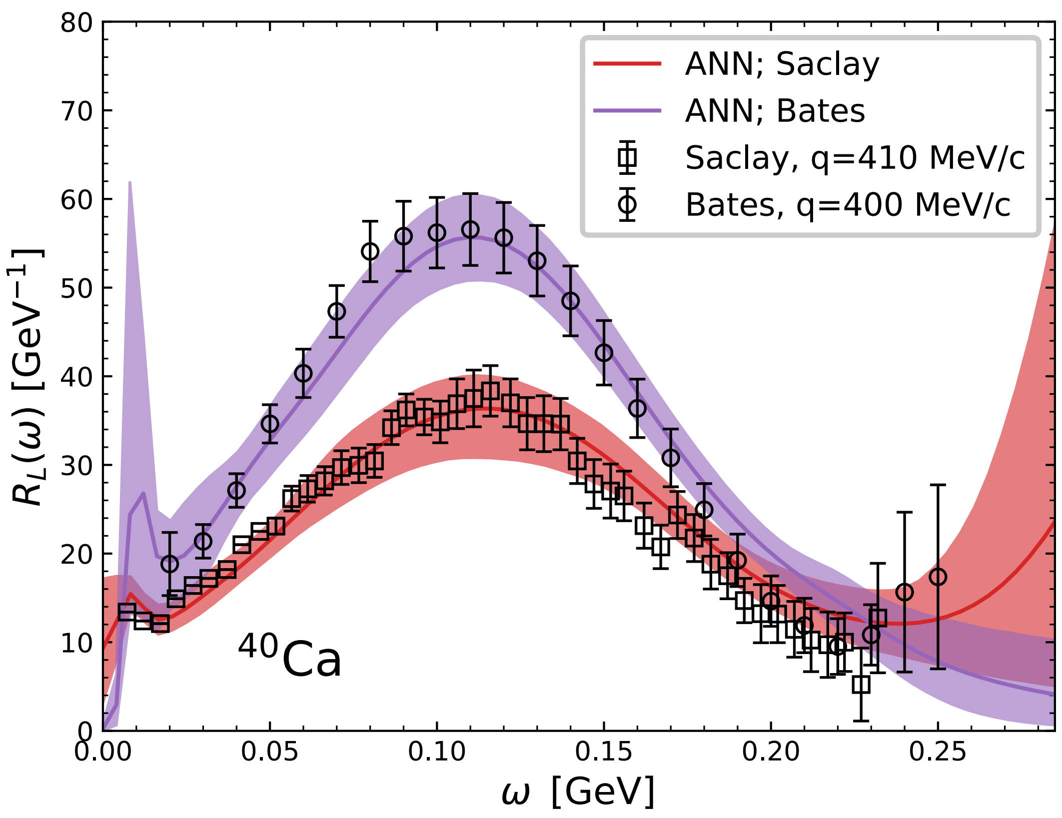
$$P(Y|\mathcal{W}) = \exp\left(-\frac{\chi^2}{2}\right)$$

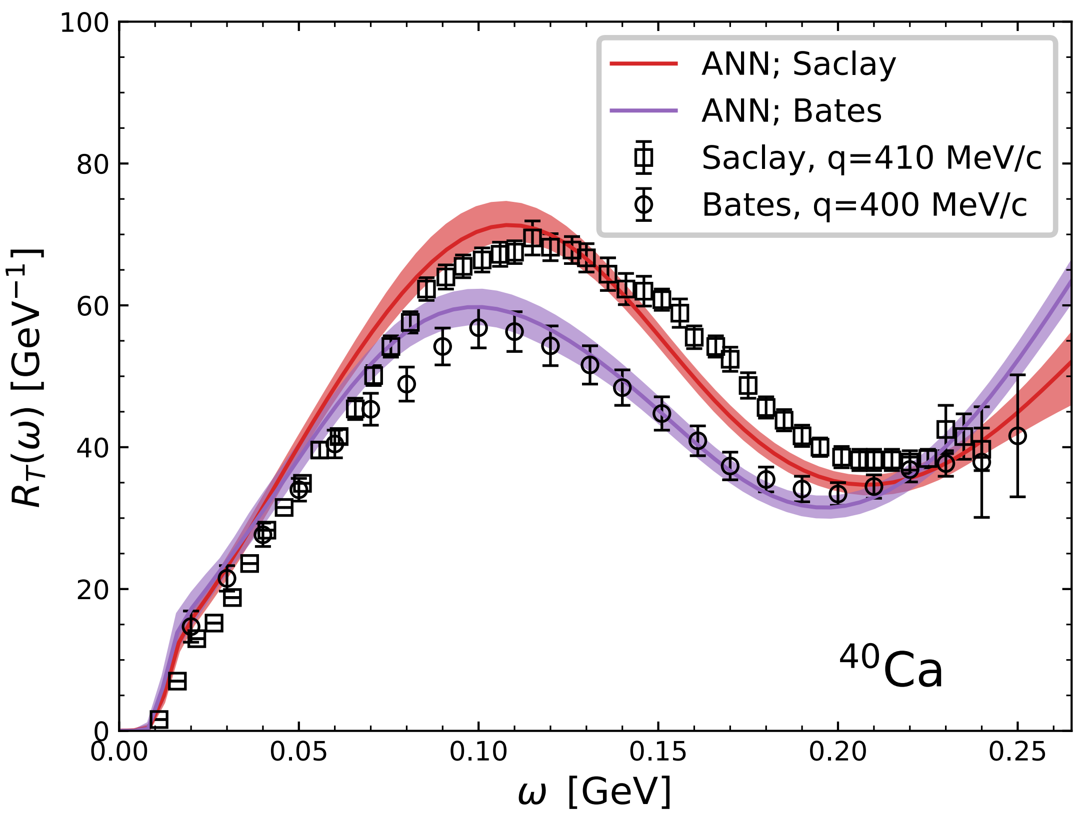


The loss function is the least-squares fit to data

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

BNN responses on ^{40}Ca





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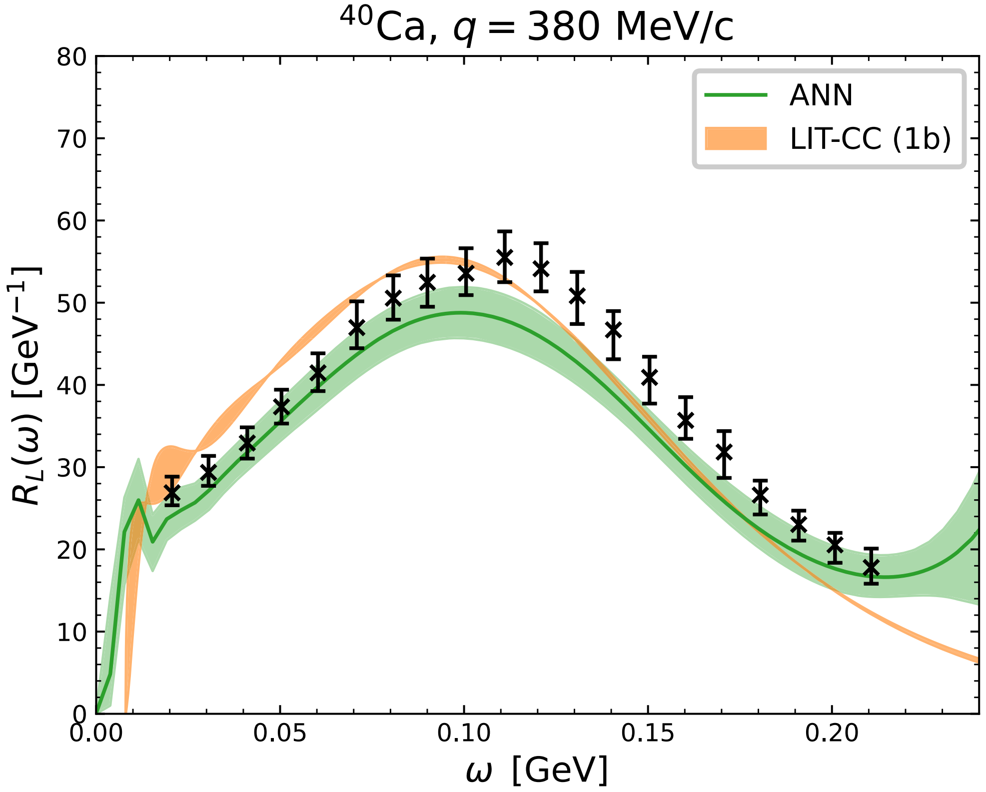

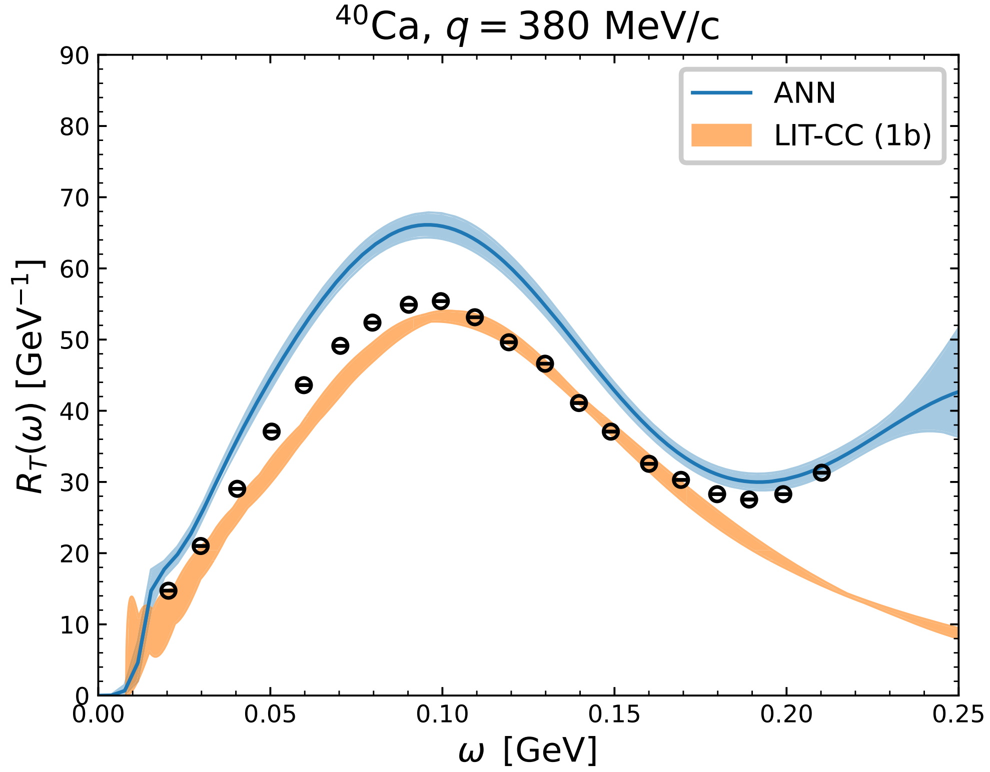

Dynamical mechanisms