TOWARDS *AB INITIO* COMPUTATIONS OF NEUTRINO SCATTERING ON MEDIUM-MASS NUCLEI

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in collaboration with
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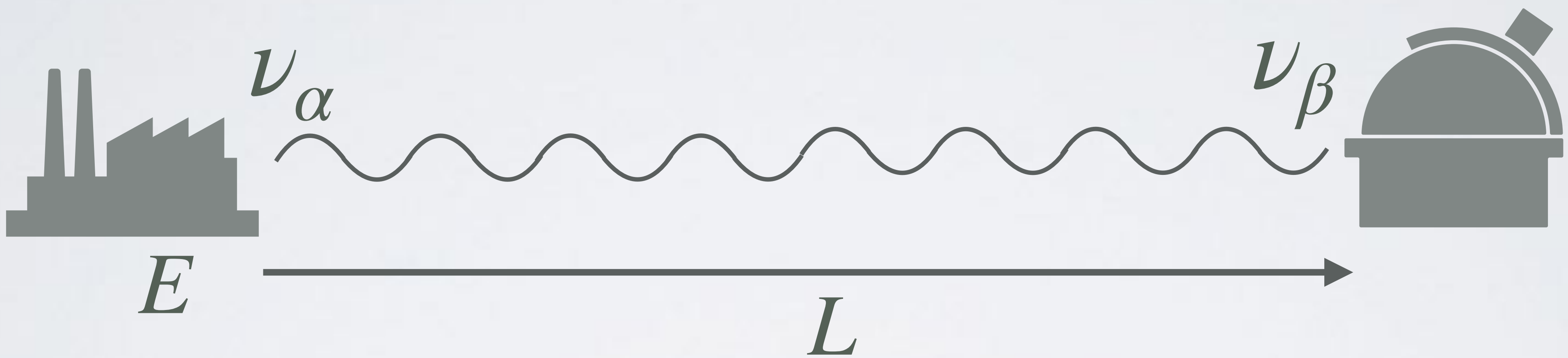
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter

OUTLINE

- Motivation: neutrino oscillation experiments and their challenges
- Neutrino-nucleus scattering in MeV-GeV region
- LIT-CC approach and first results
- Outlook

NEUTRINO OSCILLATION

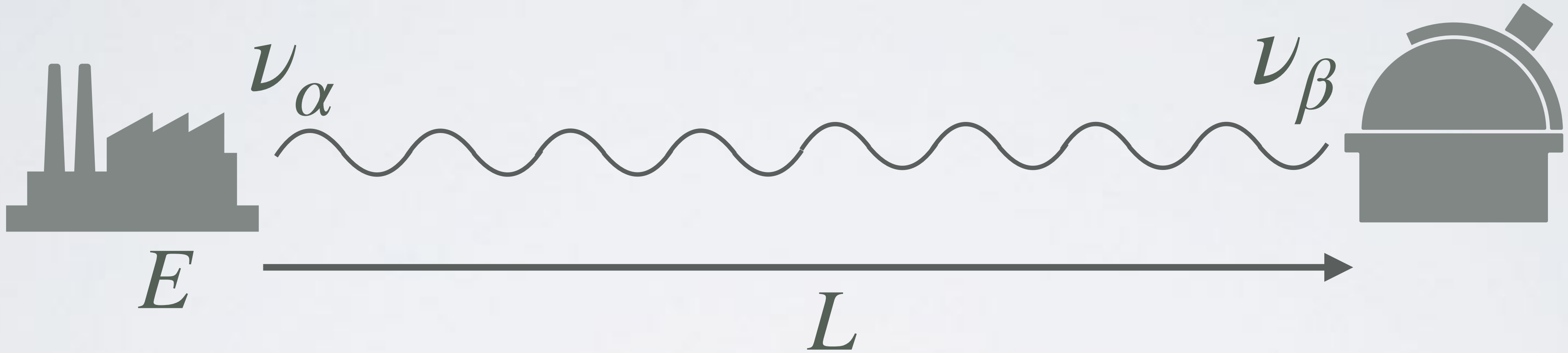


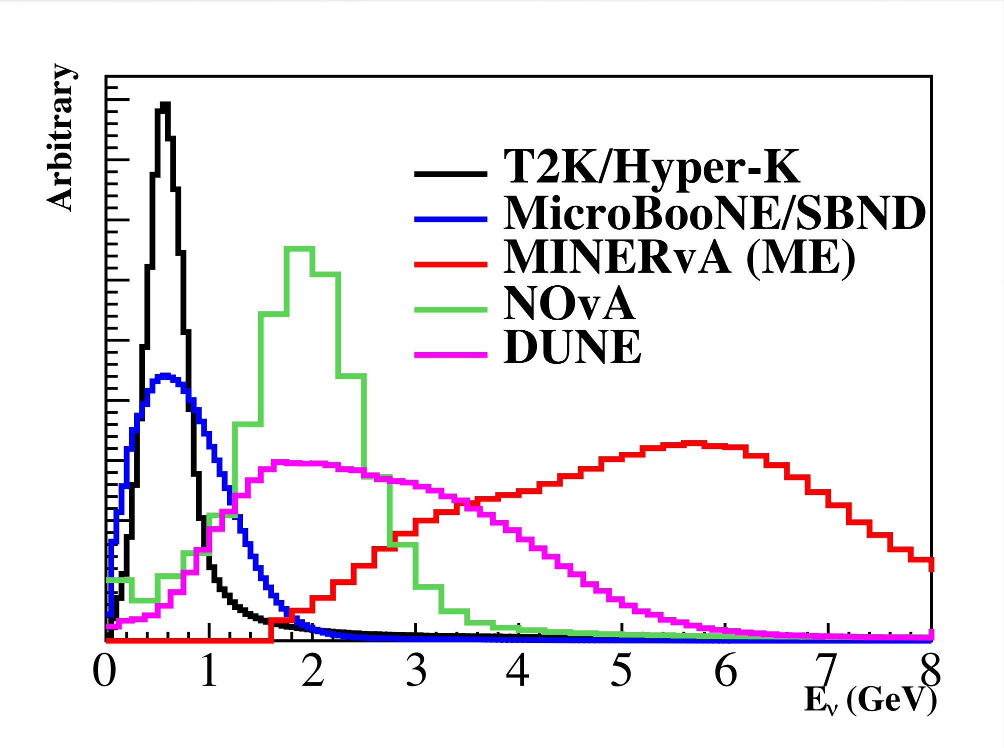
$$P(\alpha \to \beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

mixing angle (for 3 flavours we have 3 angles + CP violating phase)

experimental setup

NEUTRINO OSCILLATION



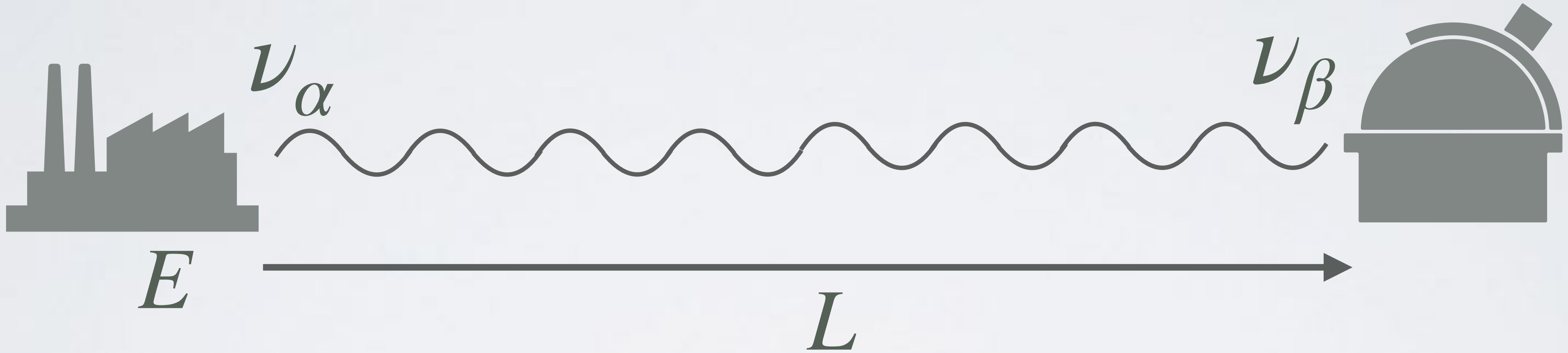


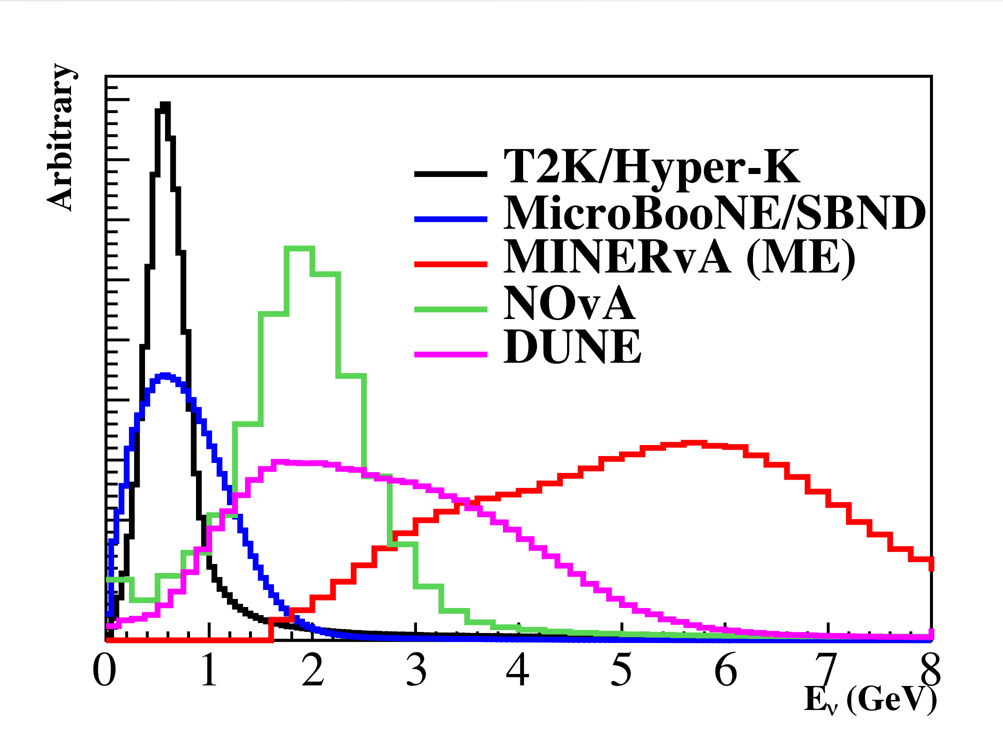
From: T. Katori, M. Martini, J.Phys. G45 (2018)

IDEA:

1. we know the initial neutrino flux (with some uncertainty)
2. we measure the rate of neutrino events in the far detector **L**
3. we have to reconstruct neutrino energy **E** and flux in the far detector

NEUTRINO OSCILLATION





From: T. Katori, M. Martini, J.Phys. G45 (2018)

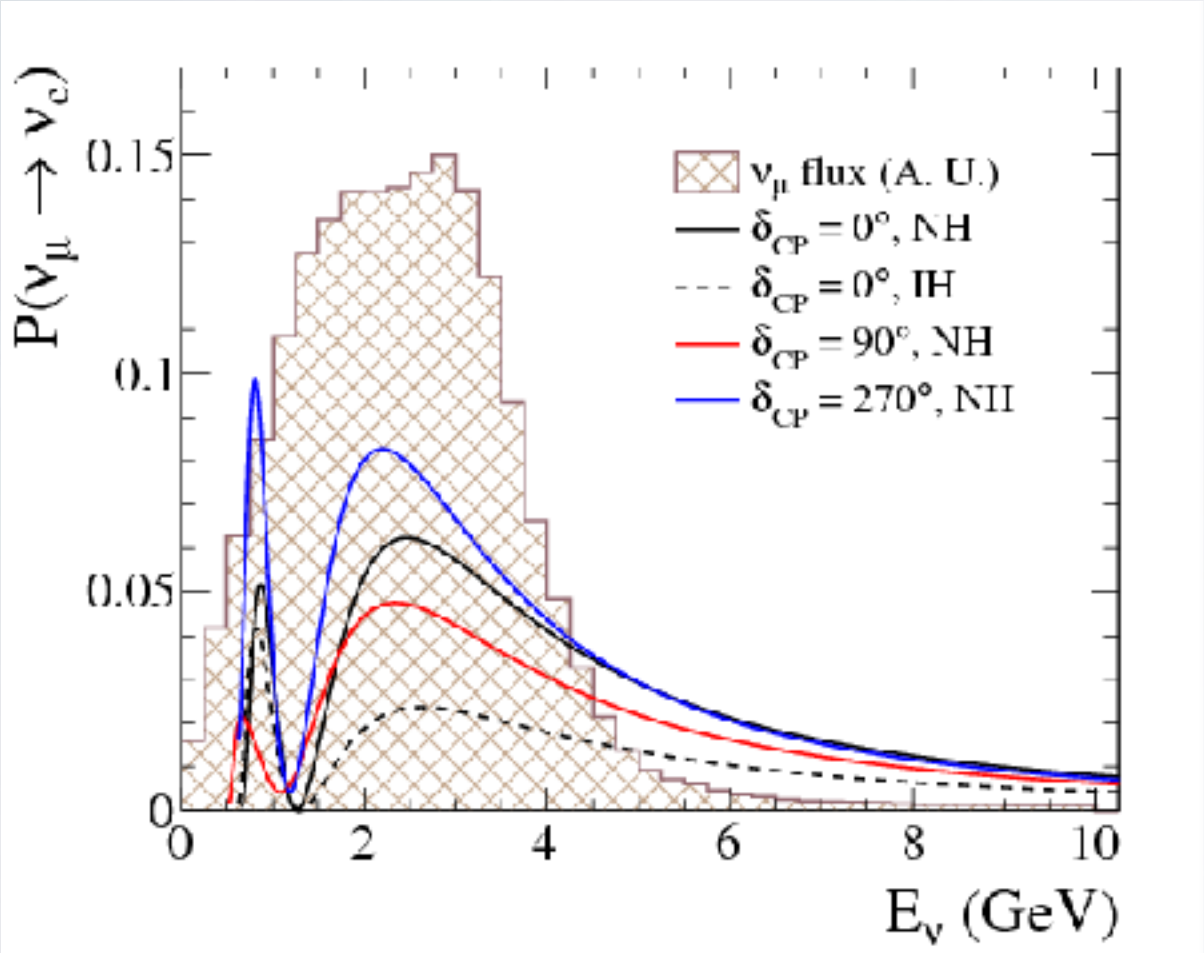
CHALLENGES:

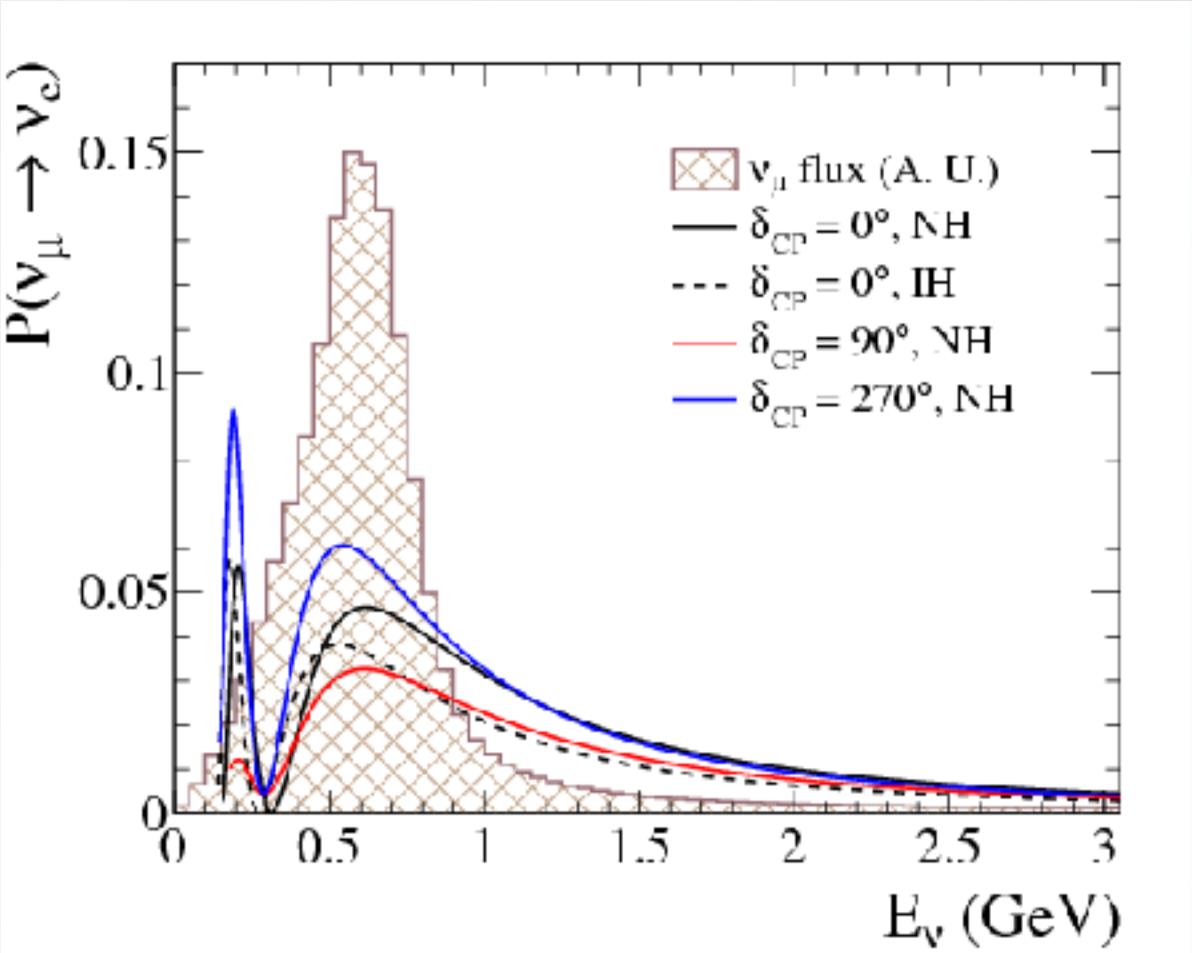
1. In each event ν is not seen
2. We observe outgoing lepton
3. Depending on the detector we see some hadrons
4. Low probability of interaction

We need theoretical predictions on how neutrino interacts with nuclei

CHALLENGES: **CP** VIOLATING PHASE

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



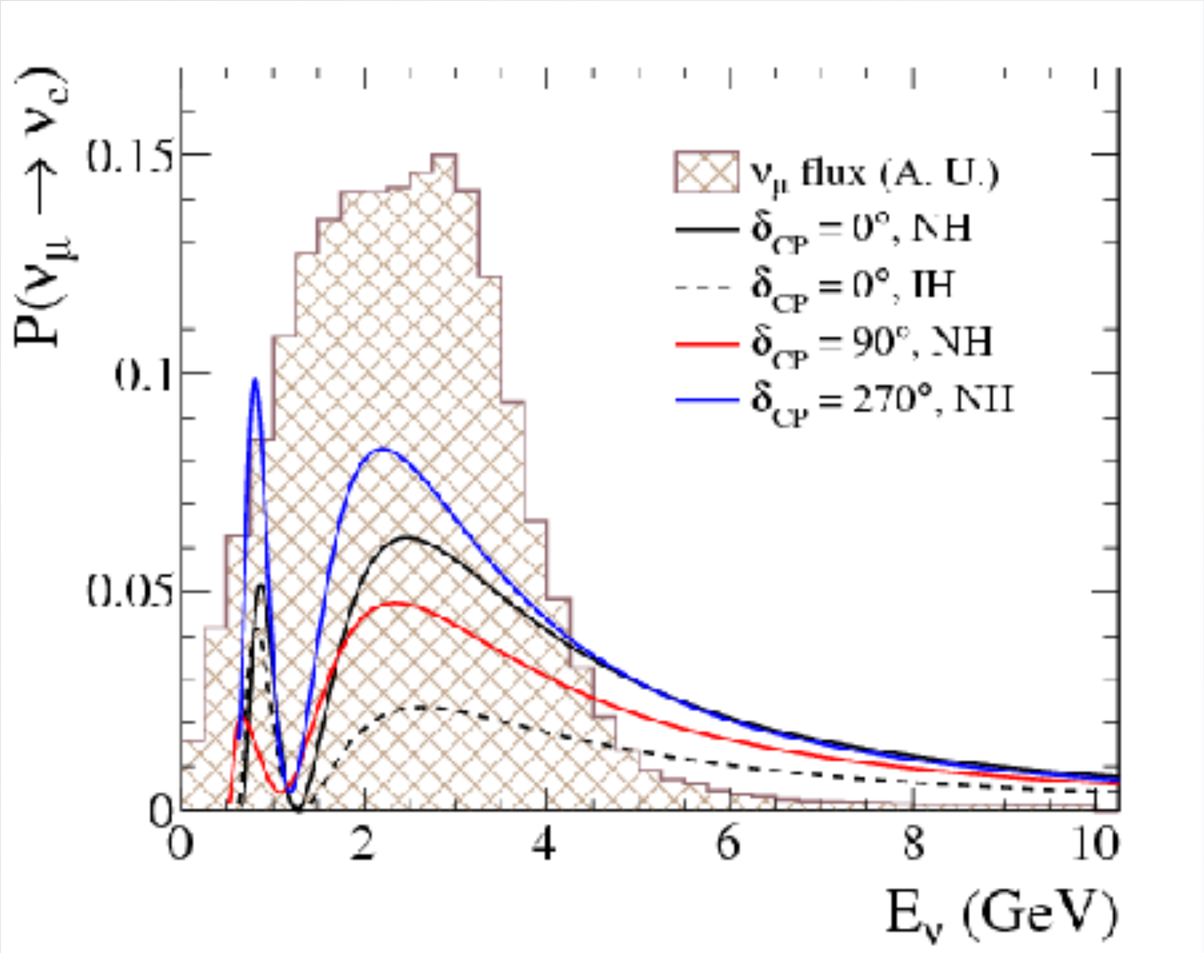


DUNE

T2HK

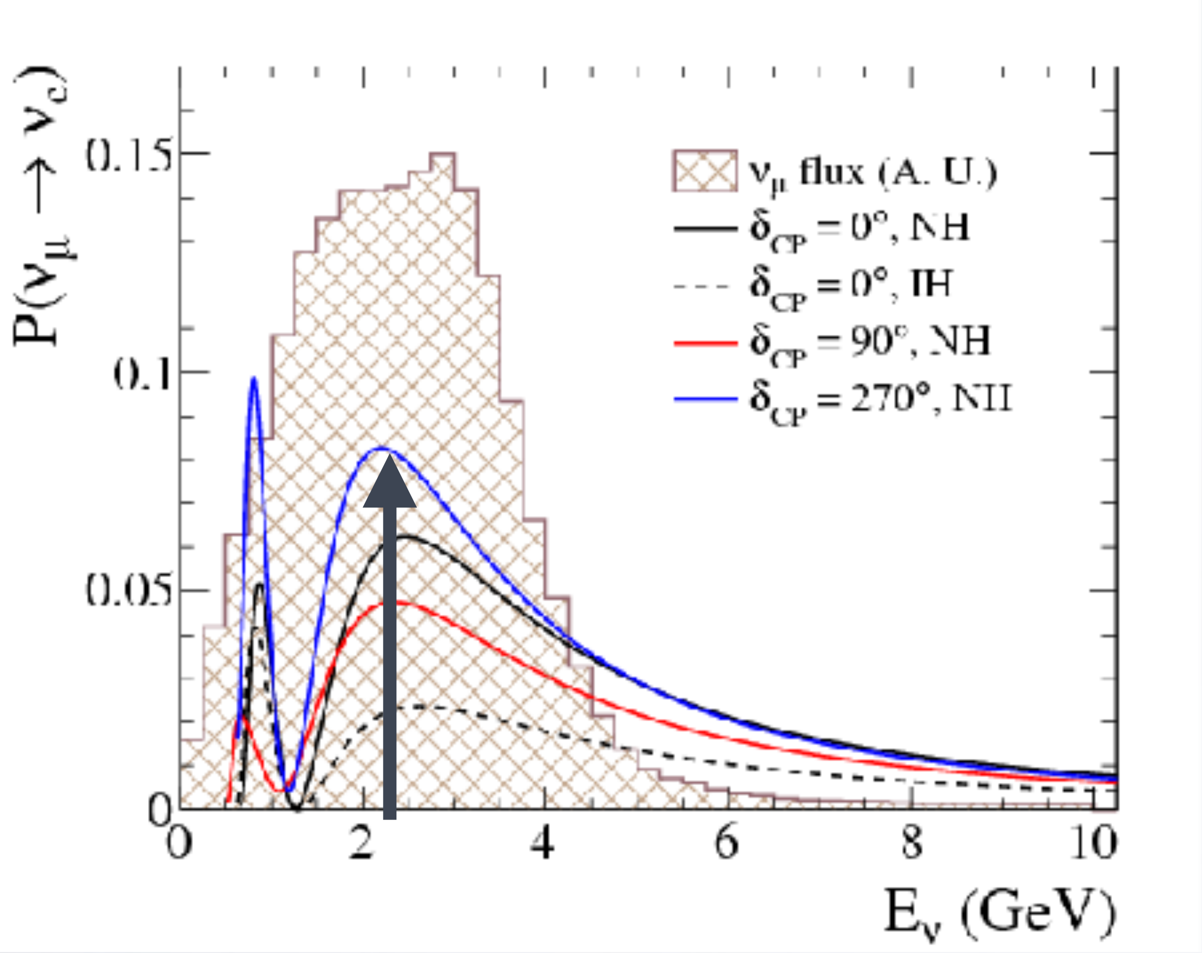
We want to reconstruct the shape of the oscillation probability curve (which depends on the CP phase)

CHALLENGES



Systematic errors should be small since statistics will be high.

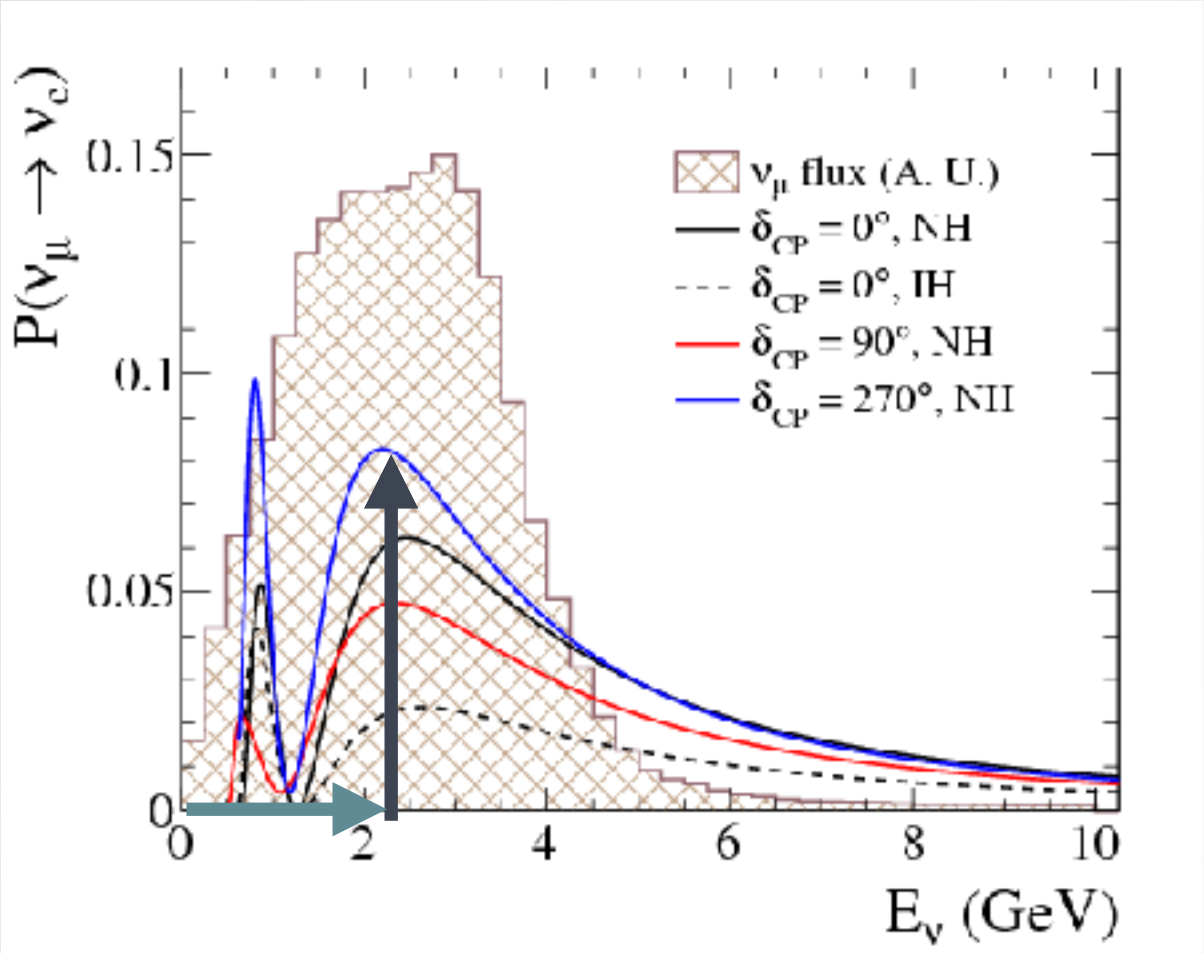
CHALLENGES



Height of the oscillation peak (event rate) ∝ total cross section

Systematic errors should be small since statistics will be high.

CHALLENGES

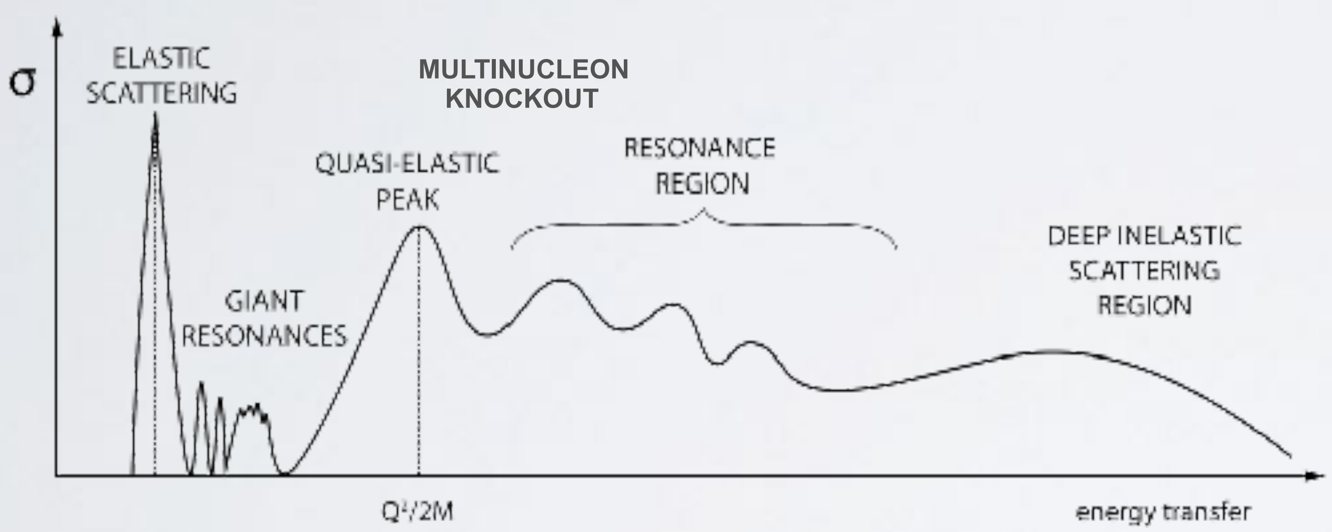


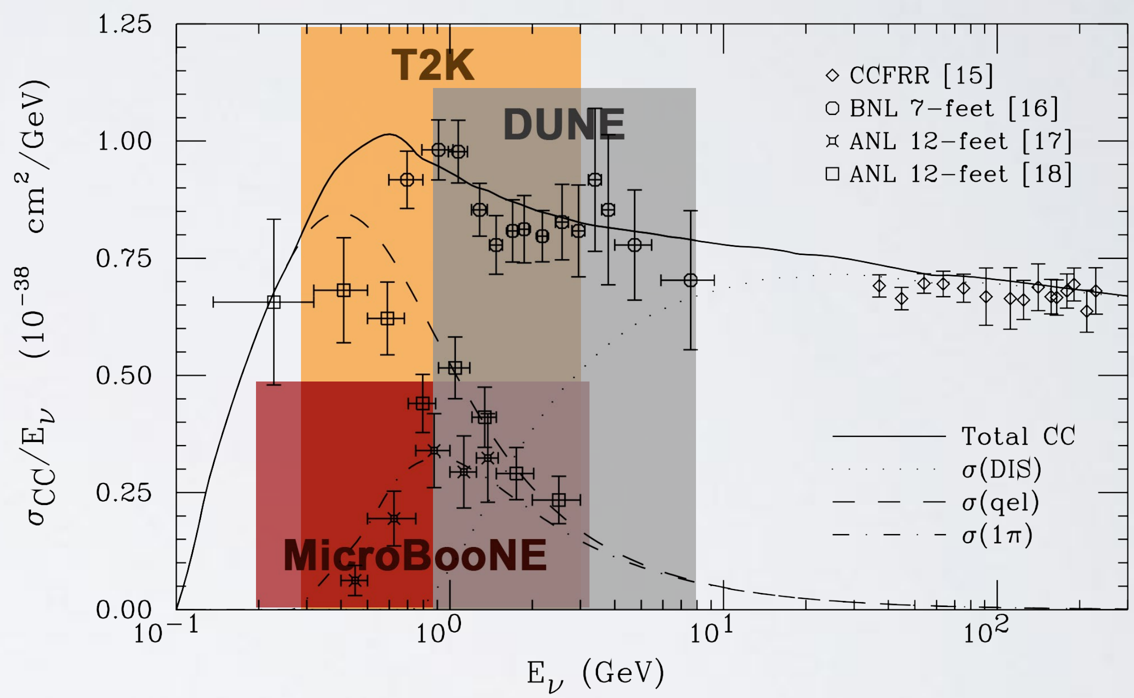
Height of the oscillation peak (event rate) ∝ total cross section

Position of the oscillation peak depends on energy reconstruction

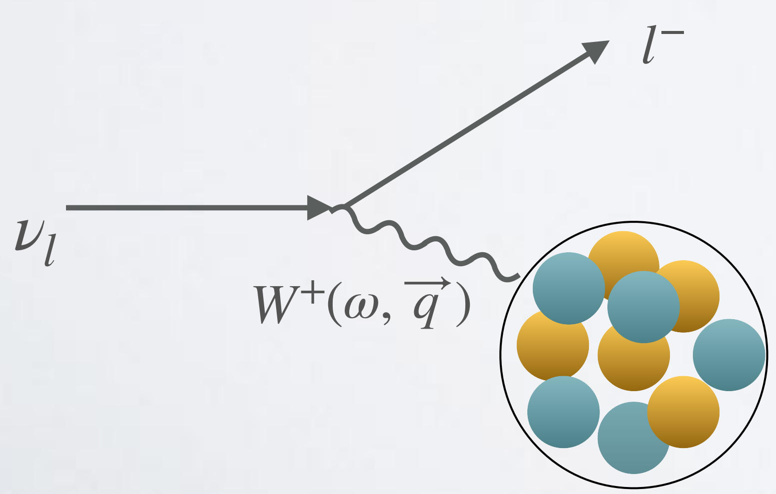
Systematic errors should be small since statistics will be high.

LEPTON-NUCLEUS SCATTERING





From: P. Lipari et. atl., PRL 74 (1995)



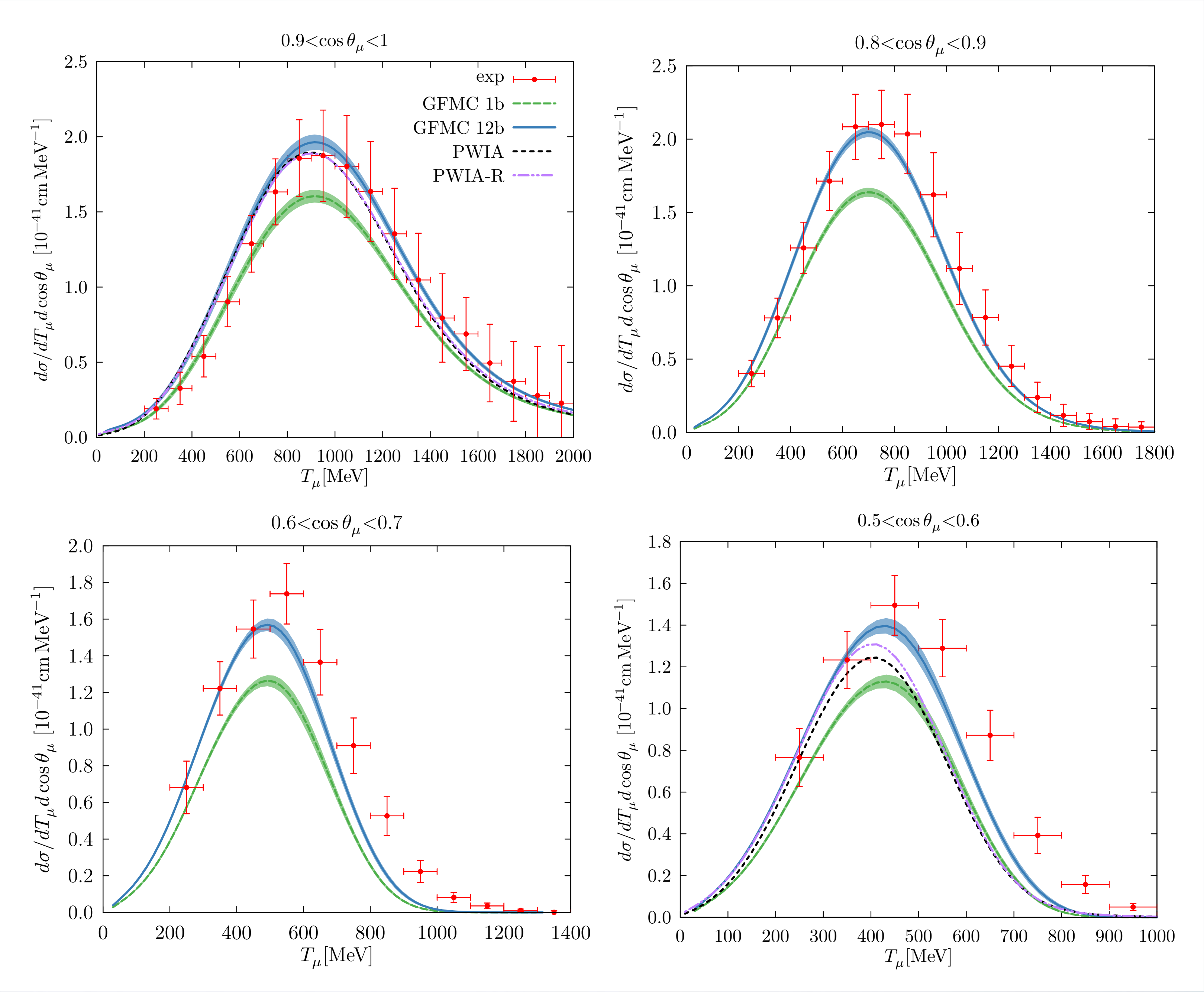
For every experiment all the physical mechanisms should be included

NUCLEAR CROSS-SECTIONS

- ✓ Theoretical models enter analysis through Monte Carlo generators
- ✓ Simpler models should be benchmarked with more reliable methods at the level of inclusive cross-section
- ✓ Important targets: ^{12}C, ^{16}O (near&far detector T2HK), ^{40}Ar (DUNE)

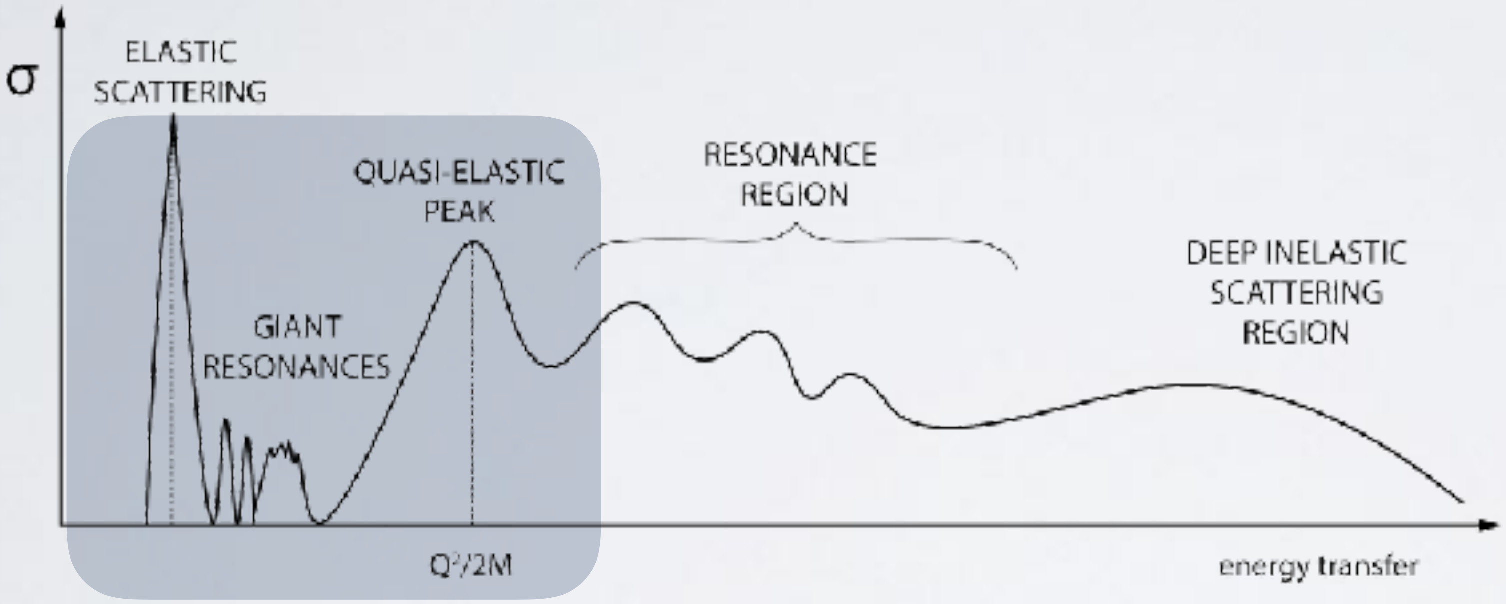
AB INITIO RESULTS FOR ^{12}C

- First GFMC comparison with experimental neutrino data
- Important contribution of 2-body currents
- GFMC suitable for light nuclei $A \leq 12$



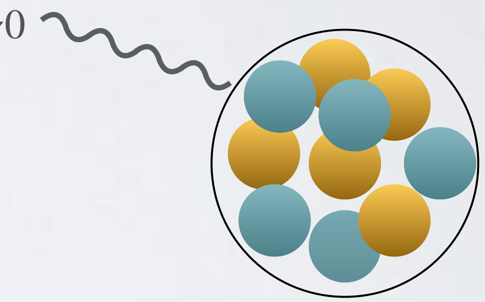
A. Lovato et al.
Phys.Rev.X 10 (2020) 3, 031068

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

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

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

→ **We will start with longitudinal response**

AB INITIO NUCLEAR THEORY FOR NEUTRINOS

✓ Nuclear Hamiltonian

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

✓ Electroweak currents

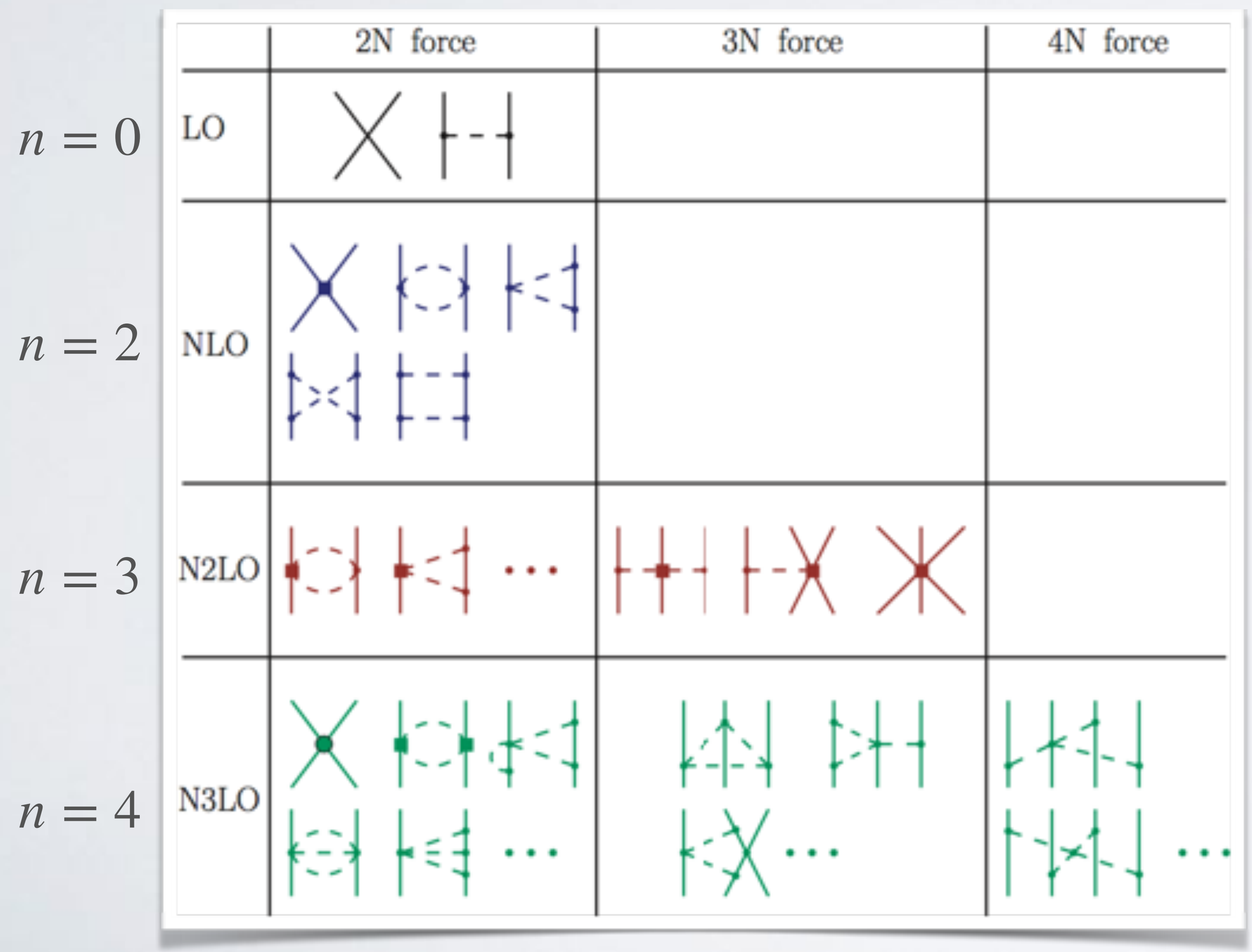
$$J^{\mu} = (\rho, \vec{j})$$

✓ Many-body method

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

NUCLEAR HAMILTONIAN

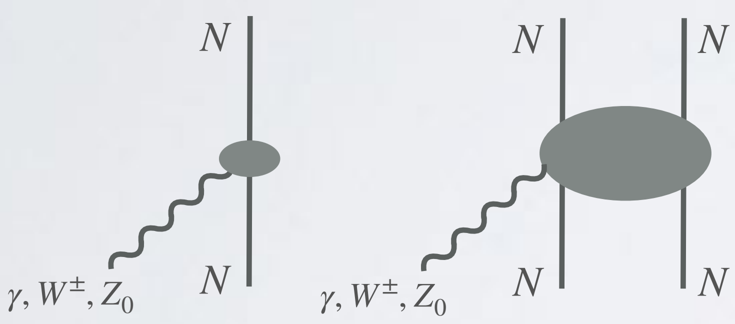
$$\mathscr{H} = \sum_i \frac{p_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$



- Chiral Hamiltonians exploiting chiral symmetry (QCD); $\pi, N, (\Delta)$ degrees of freedom
- counting scheme in $\left(\frac{Q}{\Lambda}\right)^n$
- low energy constants (LEC) fit to data
- uncertainty assessment

ELECTROWEAK CURRENTS

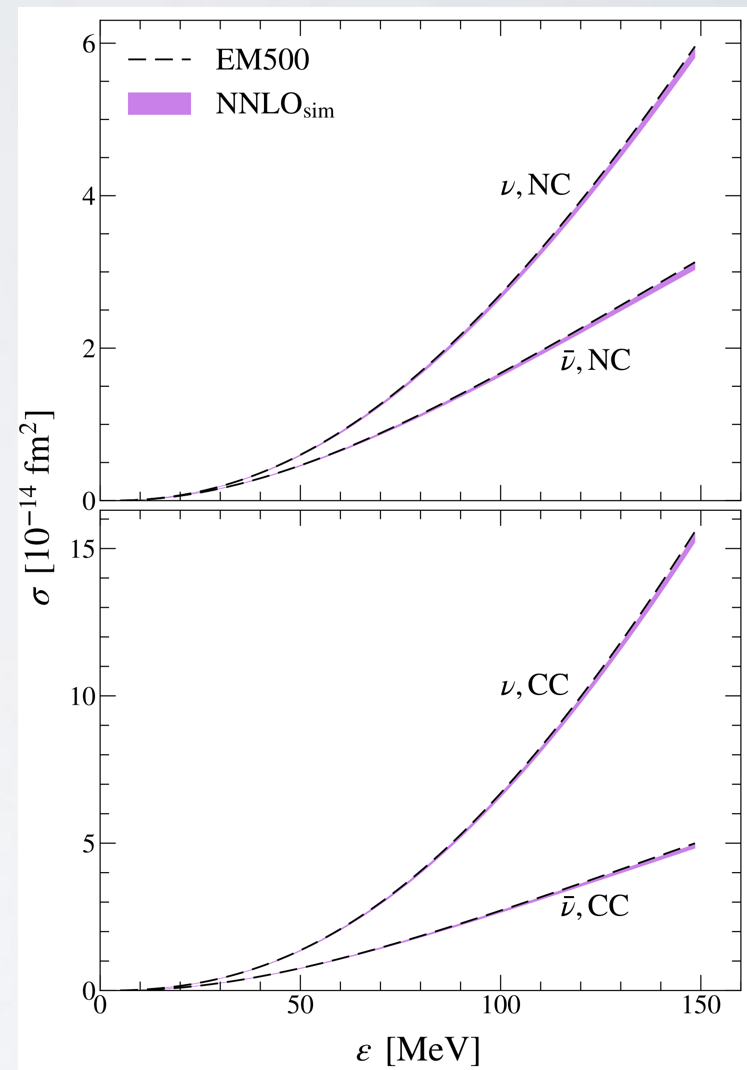
$$J = \sum_i j_i + \sum_{i<j} j_{ij} + \ldots$$



known to give significant contribution for neutrino-nucleus scattering

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

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



Multipole decomposition for 1- and 2-body EW currents

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

COUPLED CLUSTER METHOD

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

Include correlations through e^T operator

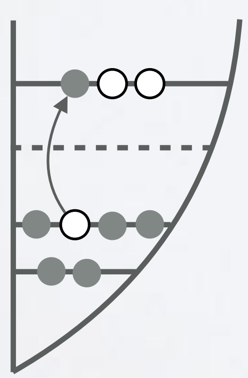
similarity transformed Hamiltonian (non-Hermitian)

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

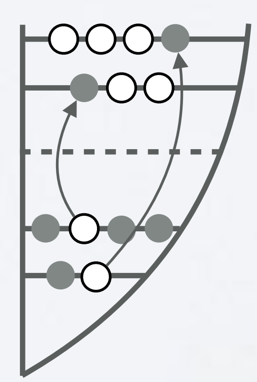
Expansion: $T = \sum t_a^i a_a^\dagger a_i + \sum t_{ab}^{ij} a_a^\dagger a_b^\dagger a_i a_j + \ldots$

←coefficients obtained through coupled cluster equations

singles



doubles



COUPLED CLUSTER METHOD

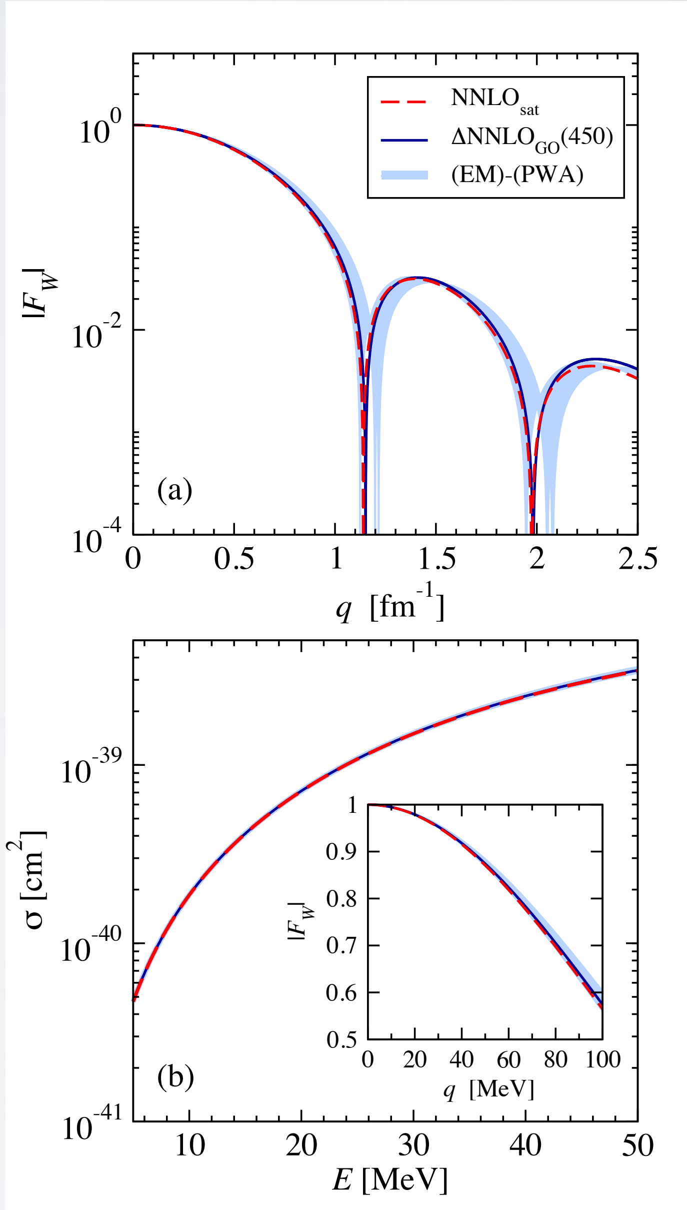
✓ Controlled approximation through truncation in T

✓ Polynomial scaling with A (predictions for ^{100}Sn)

✓ Size extensive

✓ 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

LORENTZ INTEGRAL TRANSFORM

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

continuum spectrum

Instead we calculate

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

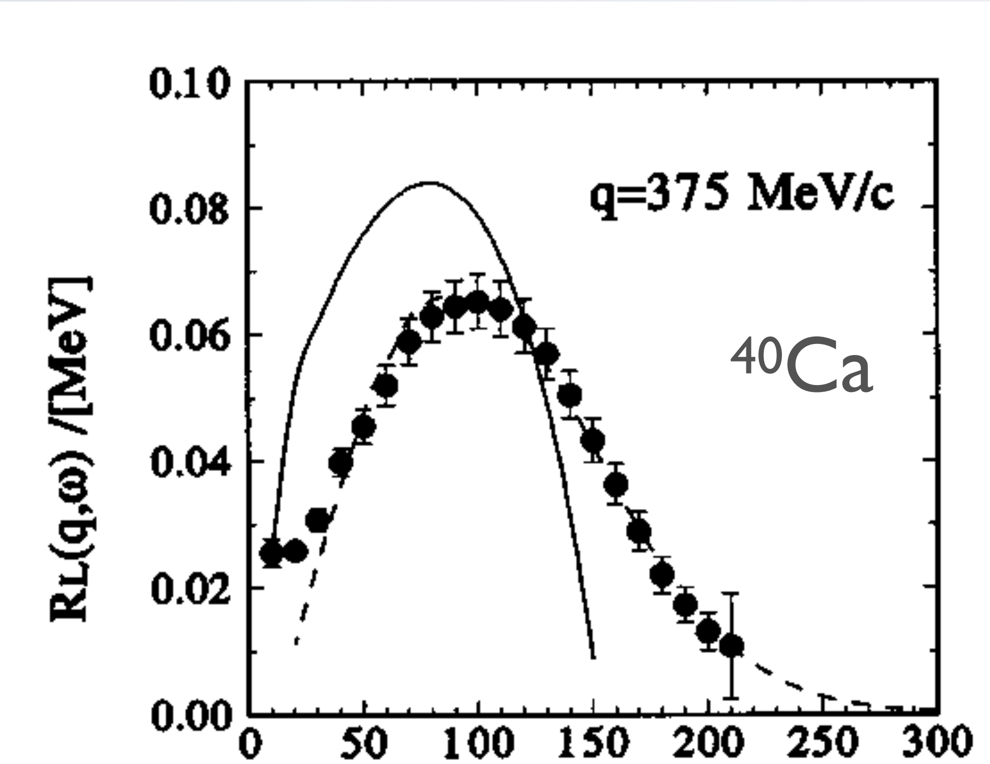
$S_{\mu\nu}$ has to be inverted to get access to $R_{\mu\nu}$

Lorentzian kernel:

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

➡ LIT-CC used for photo-absorption

LONGITUDINAL RESPONSE AND COULOMB SUM RULE



C. F. Williamson et al.
Phys.Rev.C 56, 3152-3172 (1997)

$$R_L(\omega, q) = \sum_f \langle \Psi | \hat{\rho}^\dagger(q) | \Psi_f \rangle \langle \Psi_f | \hat{\rho}(q) | \Psi \rangle \delta(E_0 + \omega - E_f)$$

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

- ➡ operator multipole decomposition (and sum)
- ➡ higher energy-momentum transfer than considered earlier
- ➡ translationally non-invariant operator

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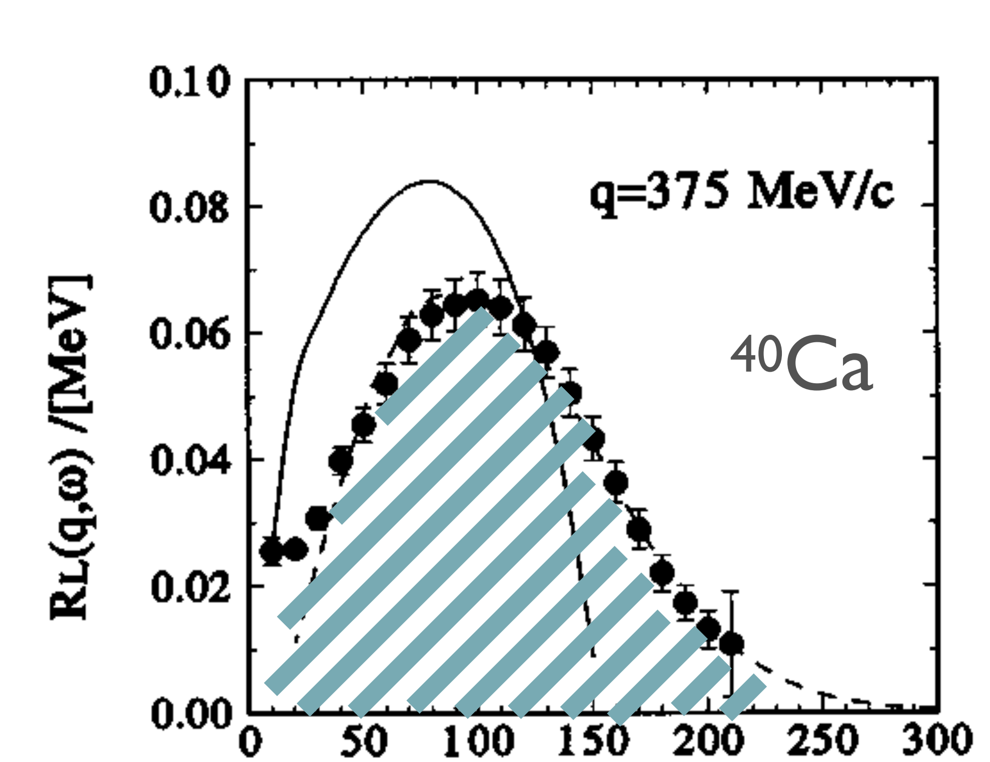

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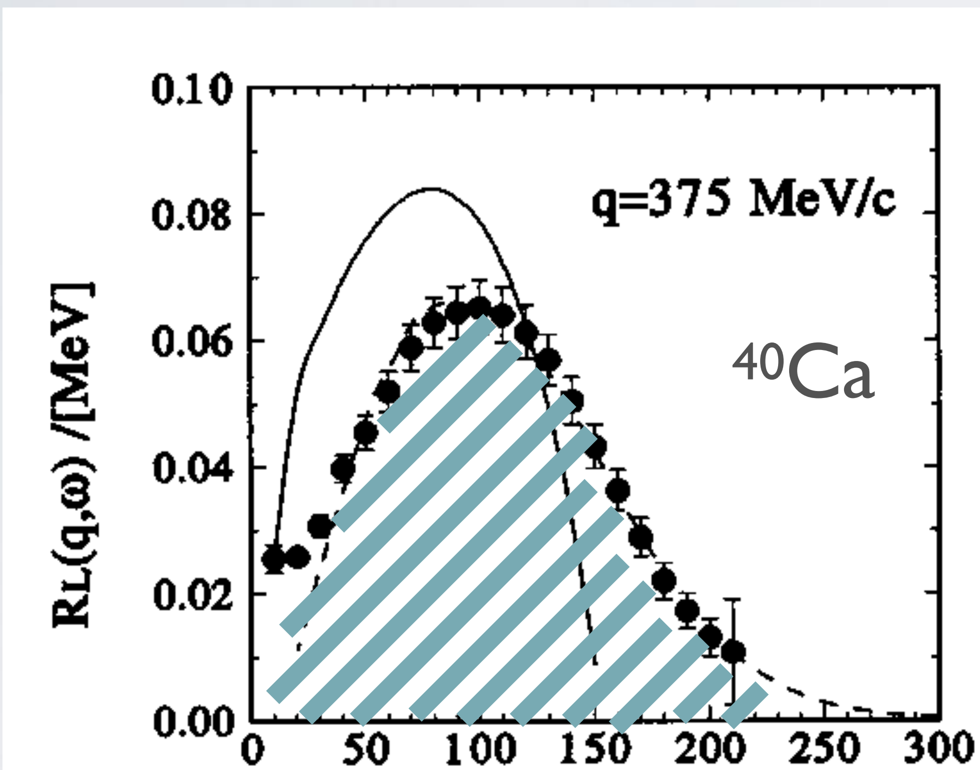

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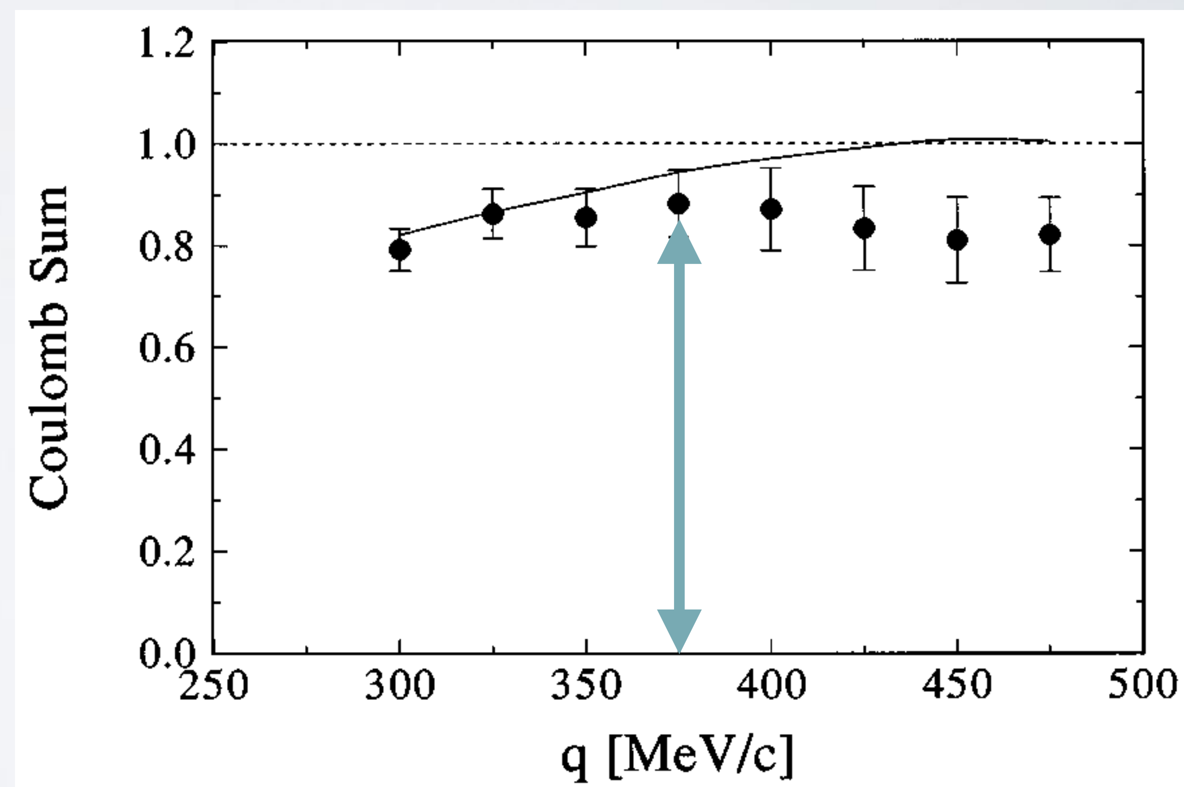

$$m_0(q) = \int d\omega R_L(\omega, q) = \sum_{f\neq 0} |\langle\Psi_f|\hat{\rho}|\Psi\rangle|^2$$

COULOMB SUM RULE

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easier to calculate since we do not need $|\Psi_f\rangle$

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center of mass problem

$|\Psi\rangle$ has 3A coordinates → 3(A-1) intrinsic coordinates + $\overrightarrow{R} = \frac{1}{A}\sum_i^A \vec{r}_i$

With translationally non-invariant operators we may excite spurious states

COULOMB SUM RULE

Project out spurious states: $\hat{\rho}\,|\Psi\rangle = |\Psi_{phys}\rangle + |\Psi_{spur}\rangle$

It has been shown that to good approximation the ground state factorizes:

$$|\Psi\rangle = |\Psi_I\rangle\,|\Psi_{CoM}\rangle$$

center of mass wave function is a Gaussian

G. Hagen, T. Papenbrock, D. Dean
Phys.Rev.Lett. 103 (2009) 062503

We follow a similar ansatz for the excited states:

$$\hat{\rho}\,|\Psi\rangle = |\Psi_I^{exc}\rangle\,|\Psi_{CoM}\rangle + |\Psi_I\rangle\,|\Psi_{CoM}^{exc}\rangle$$

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spurious

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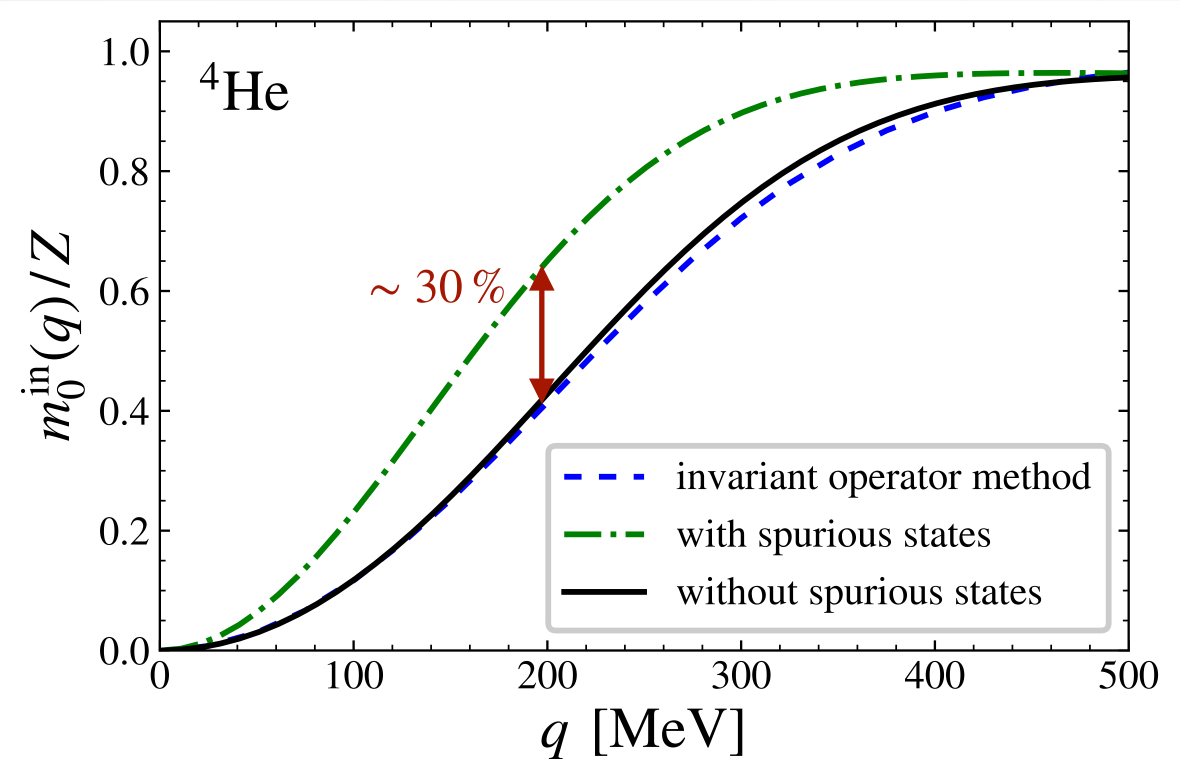
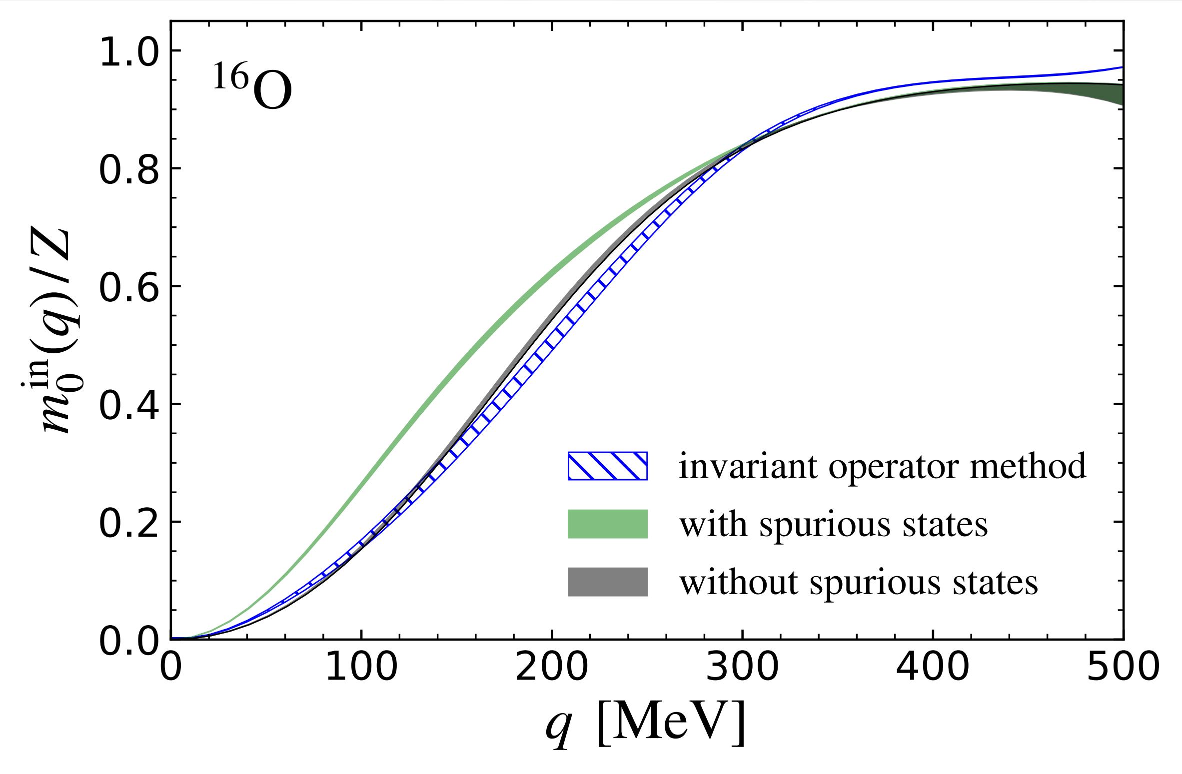
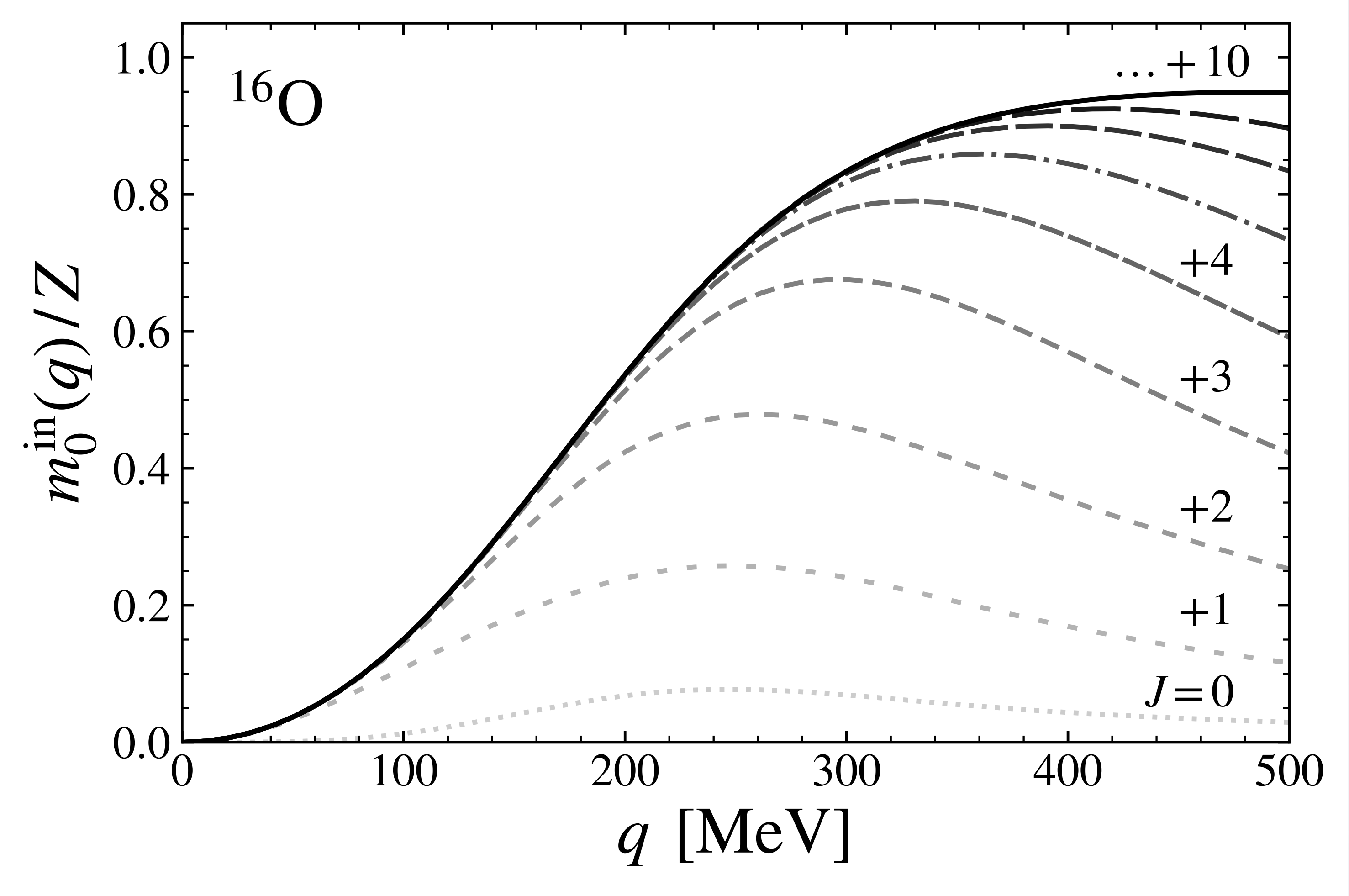




J.E.S. B. Acharya, S.Bacca, G. Hagen
Phys.Rev.C 102 (2020) 064312

CoM spurious states dominate for light nuclei

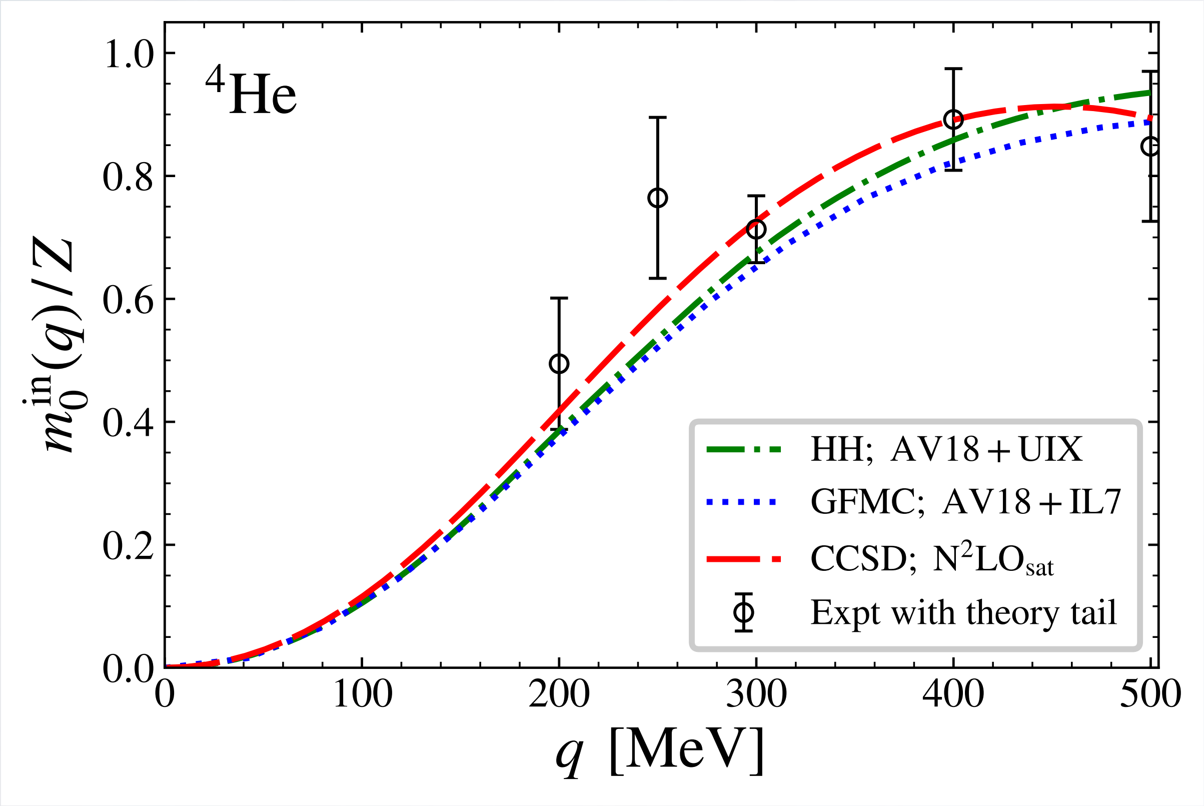
COULOMB SUM RULE

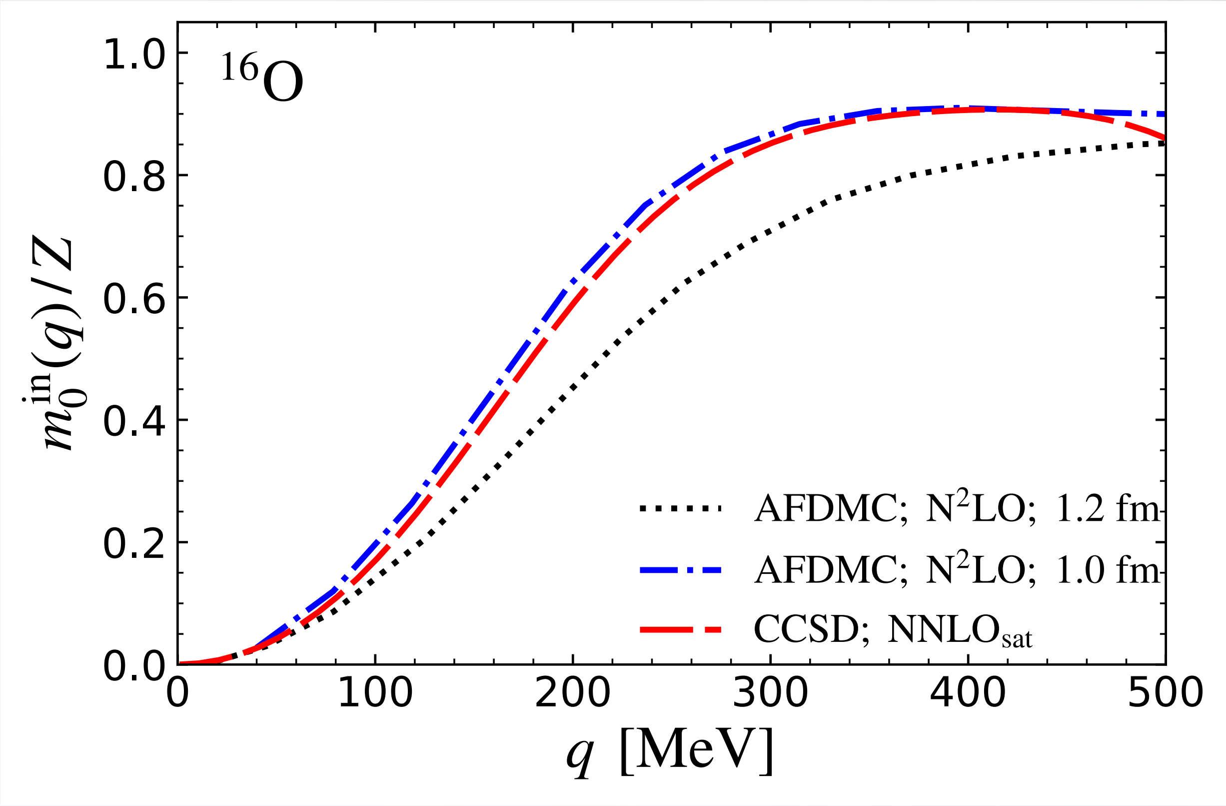


Multipole sum

$$\hat{\rho} = \sum_{J=0}^{\infty} [\hat{\rho}]^J$$

COULOMB SUM RULE





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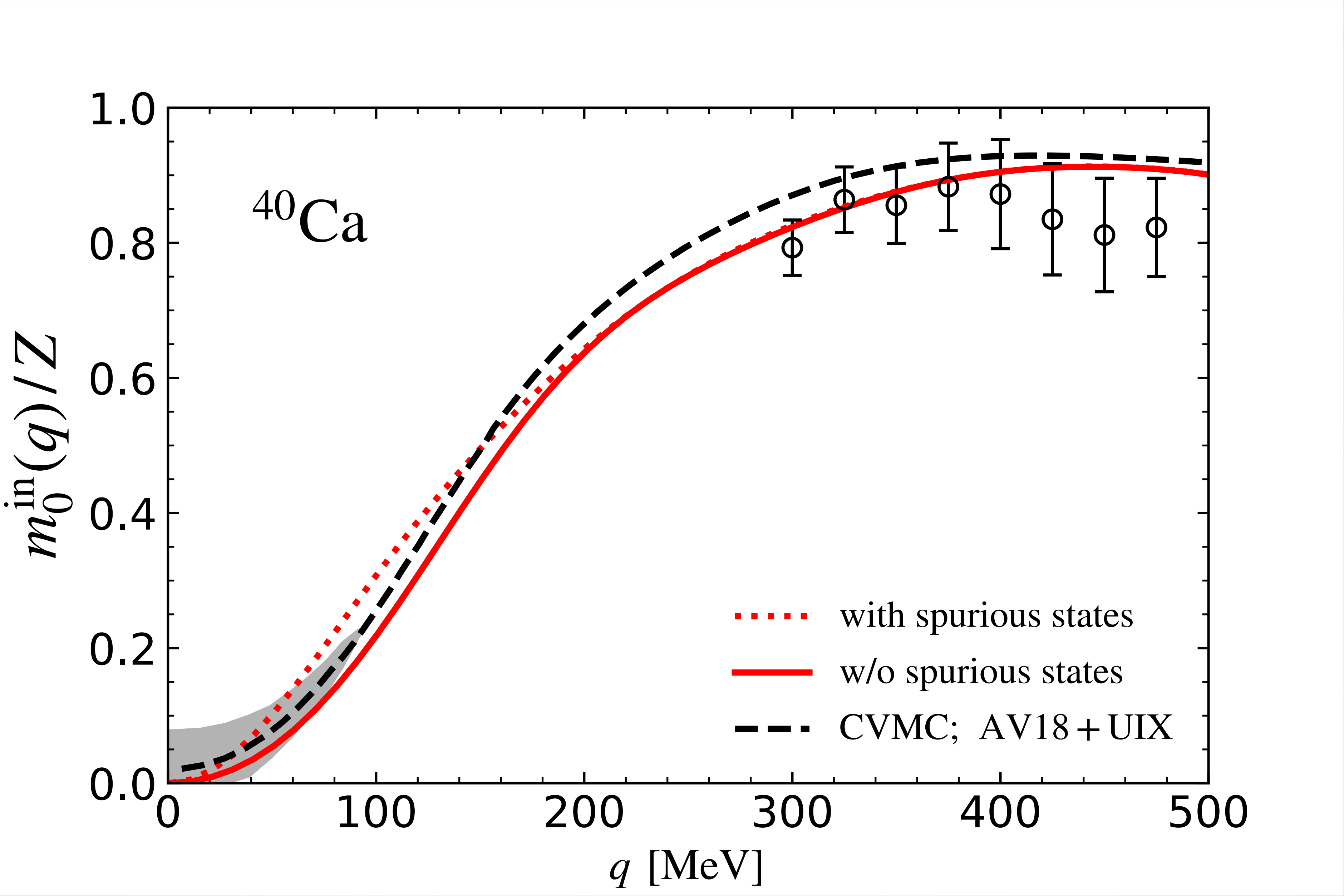
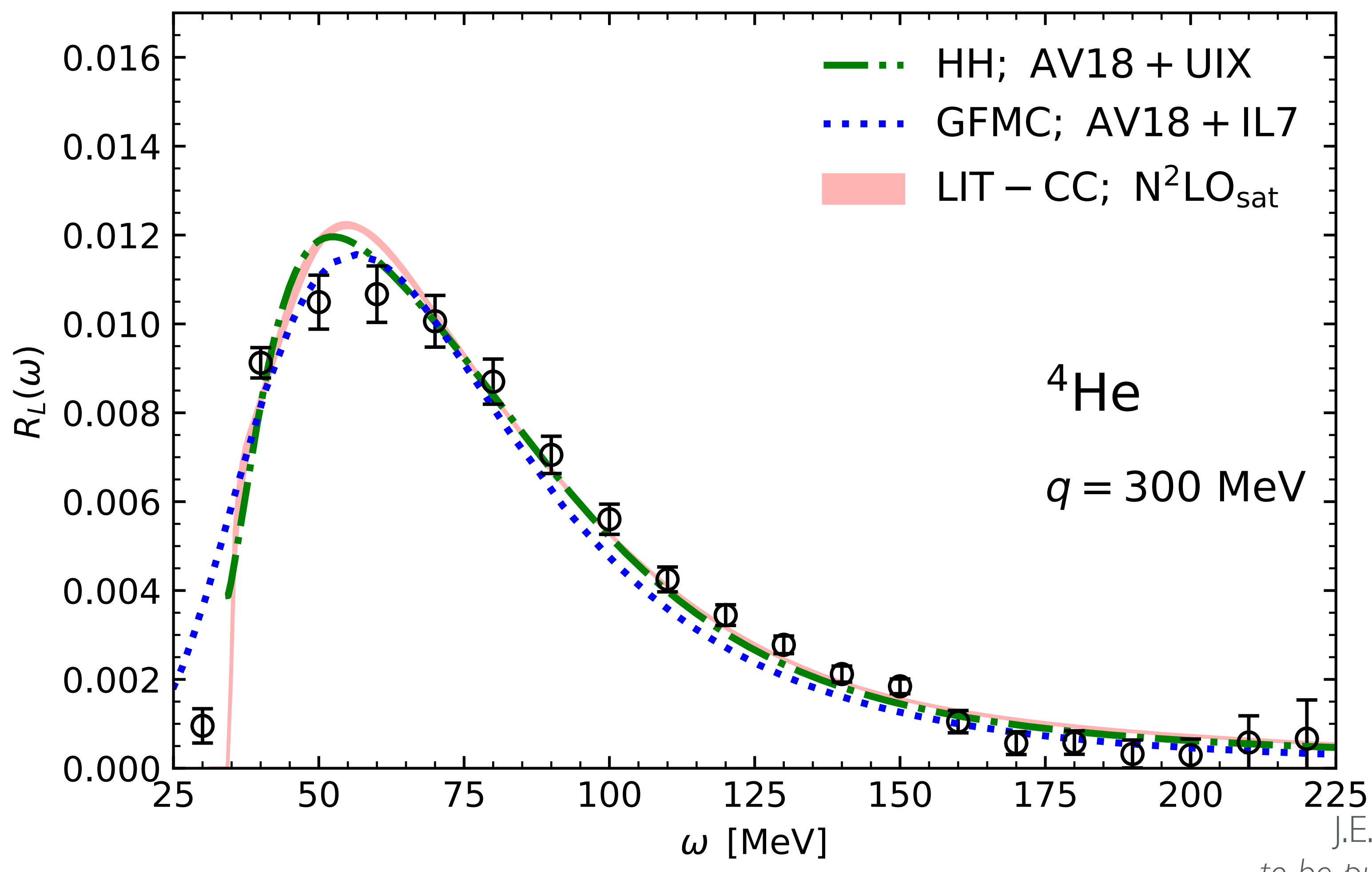


J.E.S. et al.
to be published

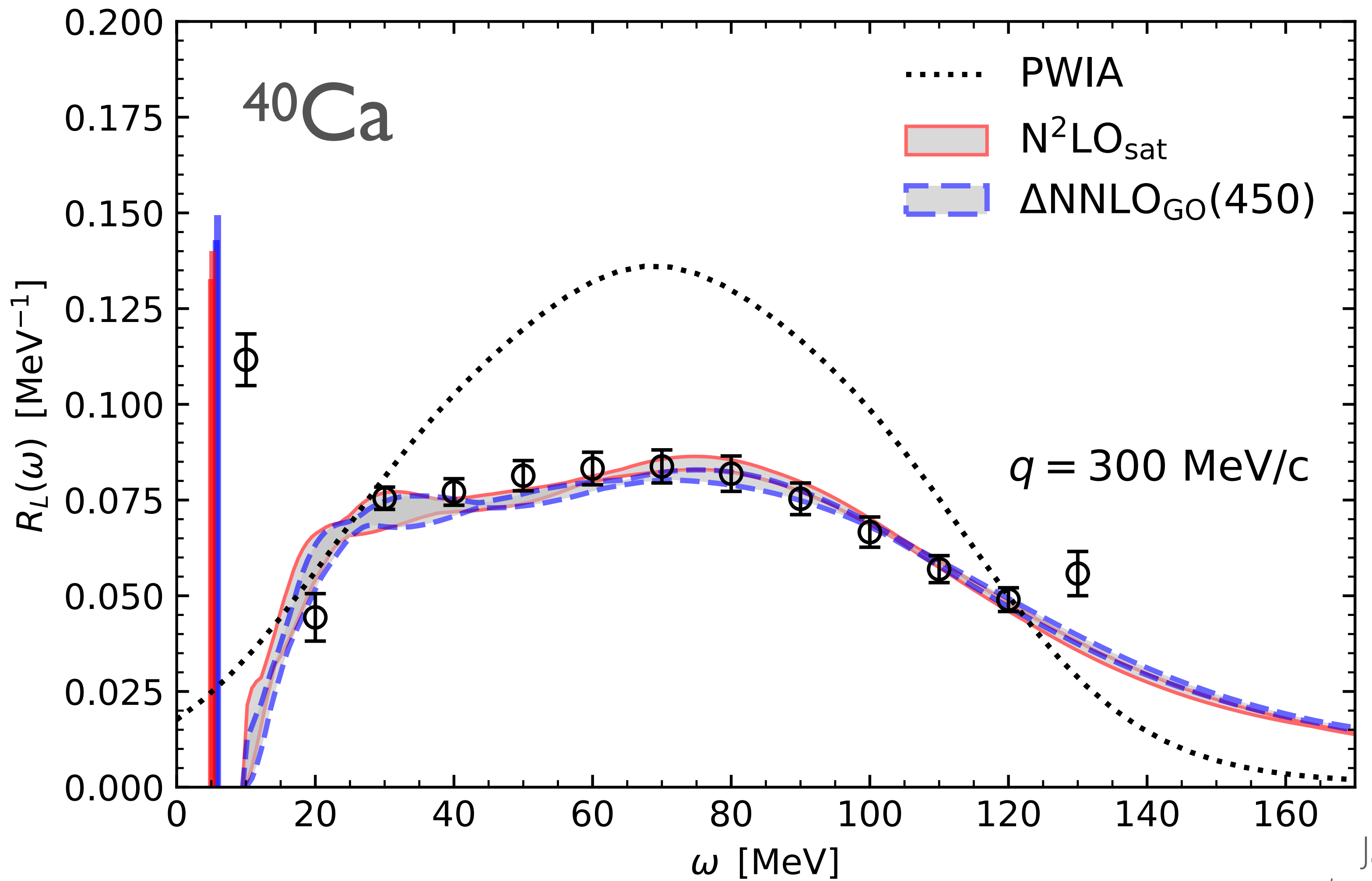
LONGITUDINAL RESPONSE



J.E.S. et al.
to be published

Uncertainty band: inversion procedure

LONGITUDINAL RESPONSE



J.E.S. et al.
to be published

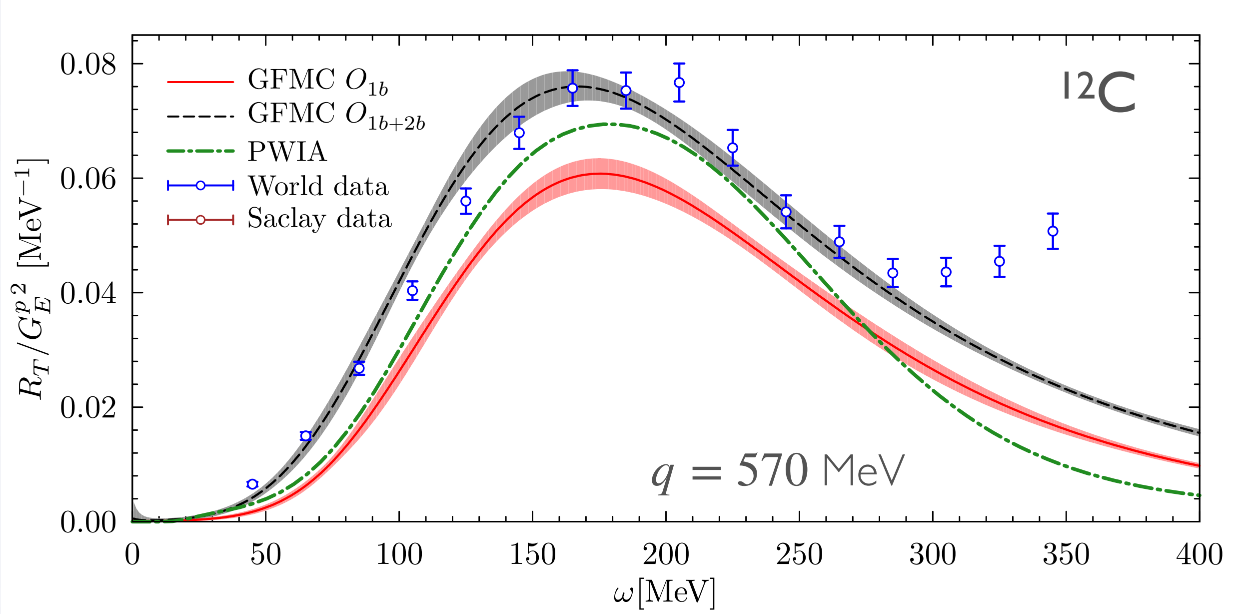
- Results for 2 different chiral potentials
- Comparison with Plane wave impulse approximation (PWIA)

OUTLOOK

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

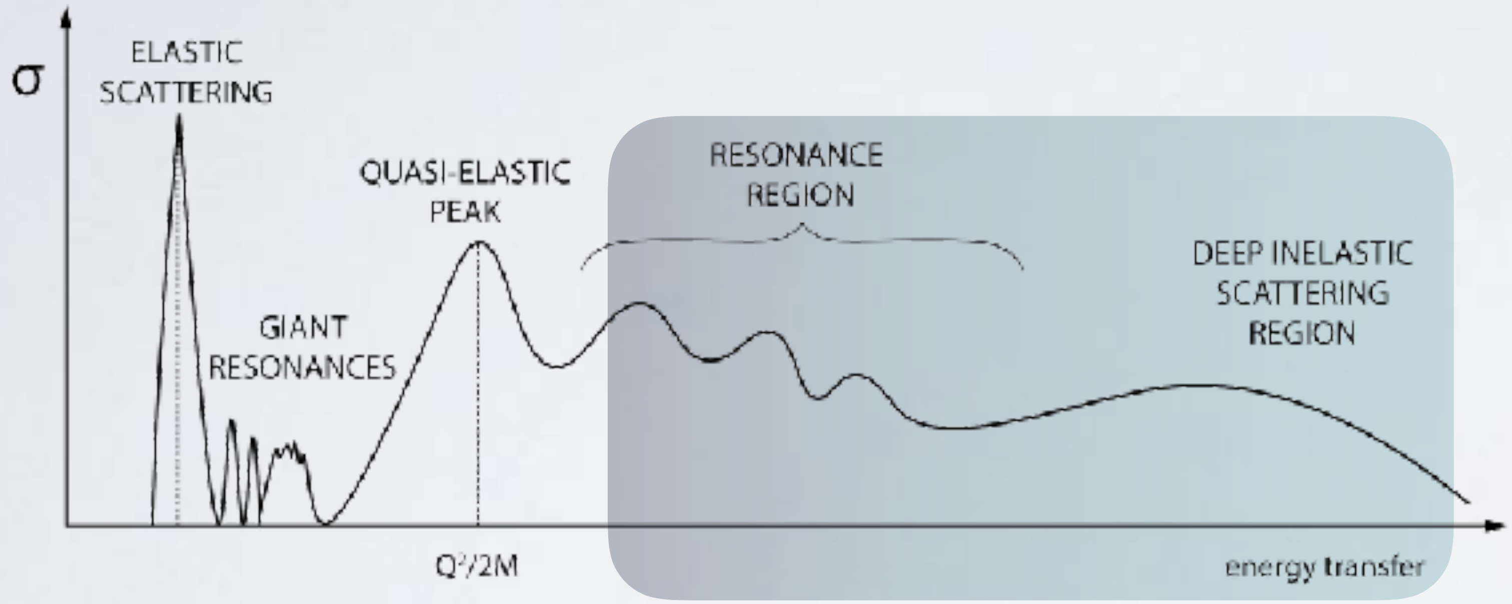
comparison with electron scattering cross-sections on ^{4}He, ^{16}O, ^{40}Ca

Transverse response (where the 2-body currents are relevant)



A. Lovato et al.
Phys.Rev.Lett. 117 (2016) 8, 082501

WHAT ELSE CAN BE DONE WITH AB INITIO THEORY?



How to account for the nuclear effects at higher energies?

<u>Impulse Approximation</u>
is valid when q is high enough (resolution+final state interaction negligible).

<u>Spectral function</u>
Probability distribution of finding a nucleon of a given momentum and energy in the nucleus.

CONCLUSIONS

- Nuclear physics is challenged by neutrino oscillation experiments
- Setting stage for neutrino-nucleus cross-section calculation:
  - 2-body currents decomposition into multipoles
  - removal of spurious states
  - application of LIT-CC method for momentum transfer $q \leq 500$ MeV
- With LIT-CC we obtained first ab initio results for longitudinal response for medium-size nuclei (^{16}O and ^{40}Ar can be addressed)

THANK YOU