Neutrino-Nucleus Scattering (overview of microscopic approach)

J. Carlson (LANL)
May, 2019

in collaboration with:
A. Lovato
S. Pastore
S. Gandolfi
D. Lonardoni
S. C. Pieper
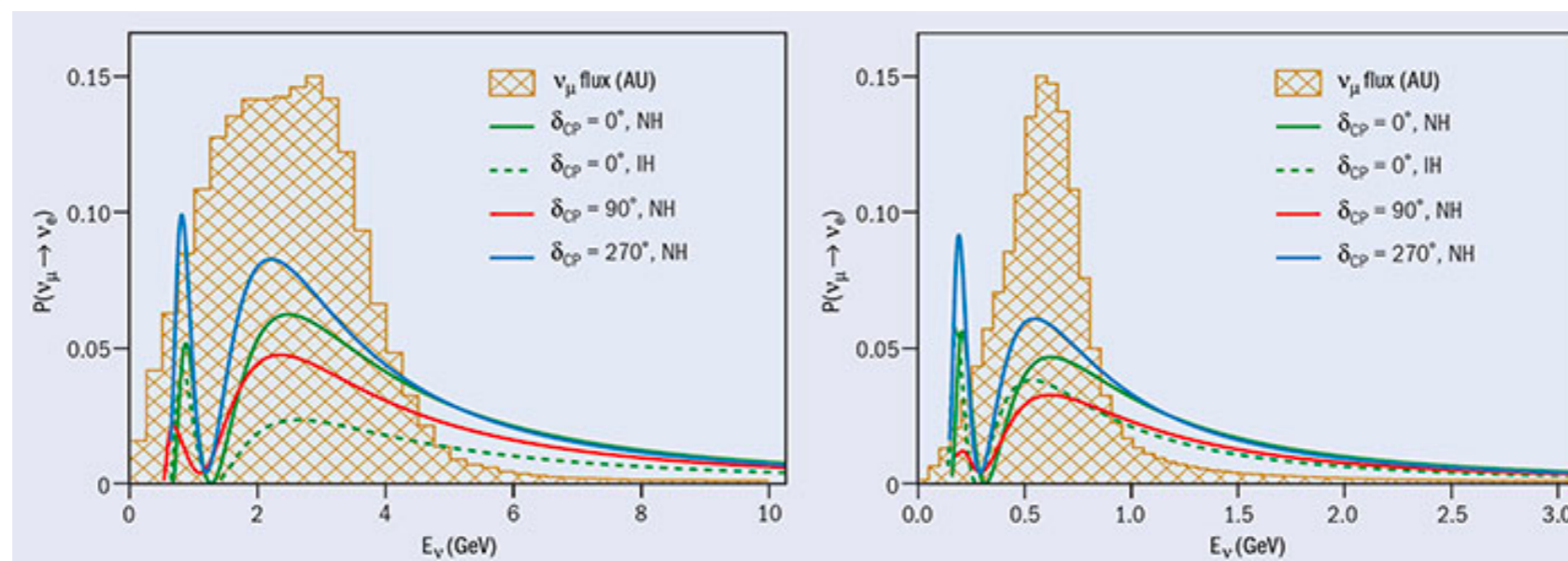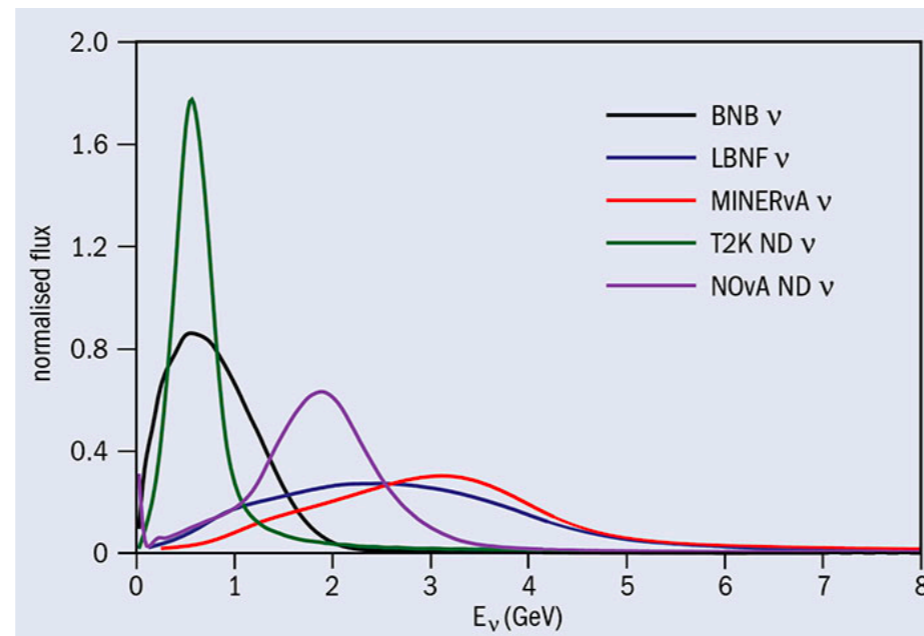N. Rocco
A. Roggero
R. Schiavilla
R. B. Wiringa

- Motivation
- Interactions/Currents
- Inclusive Electron Scattering
- Short-time Evolution
  and two-nucleon dynamics
- Summary / Outlook

Accelerator Neutrino Experiments
wide range of neutrino energies
importance of oscillations/cross sections for energies ~1-3 GeV
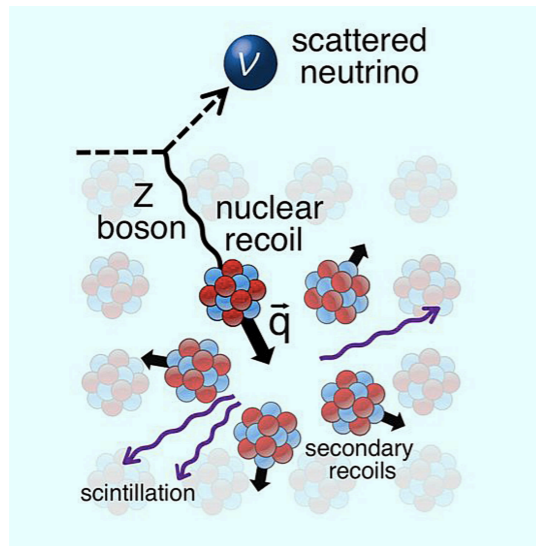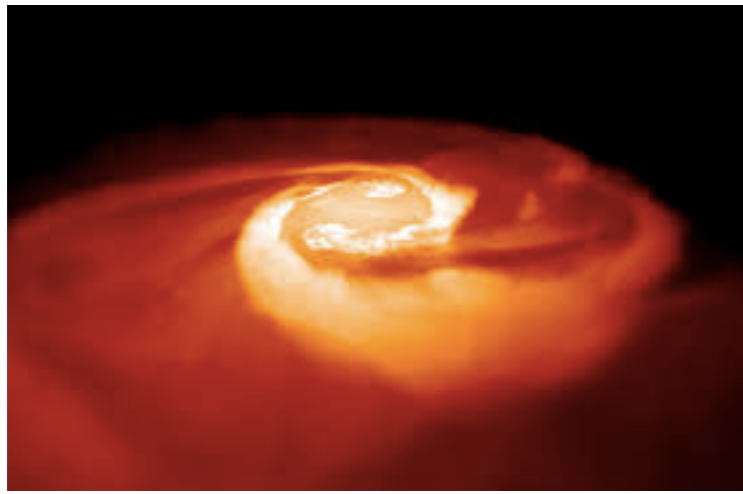

DUNE

T2K

Why study Neutrinos and Nuclei

Neutrinos and nuclei are fundamental to some of the largest and most exciting experiments and observations
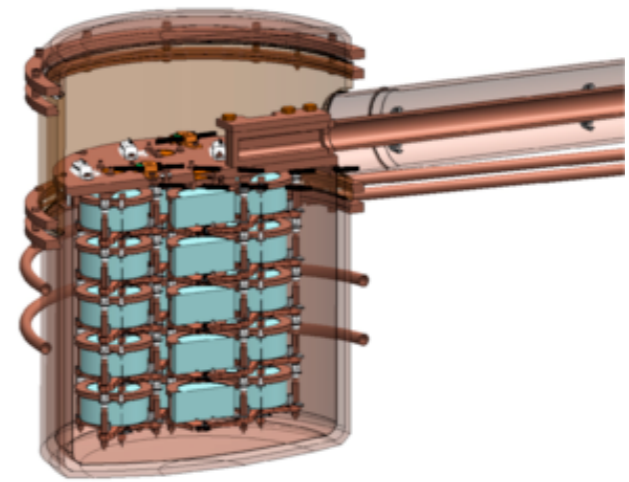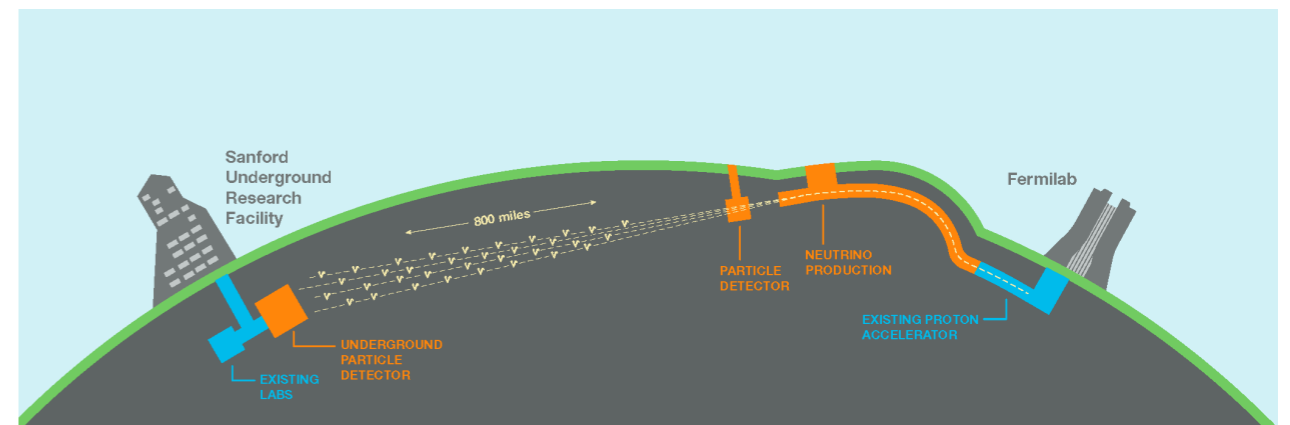
Coherent neutrino scattering at SNS

Supernovae/ Neutron star mergers and nucleosynthesis

Double Beta decay
Majorana nature of the neutrino
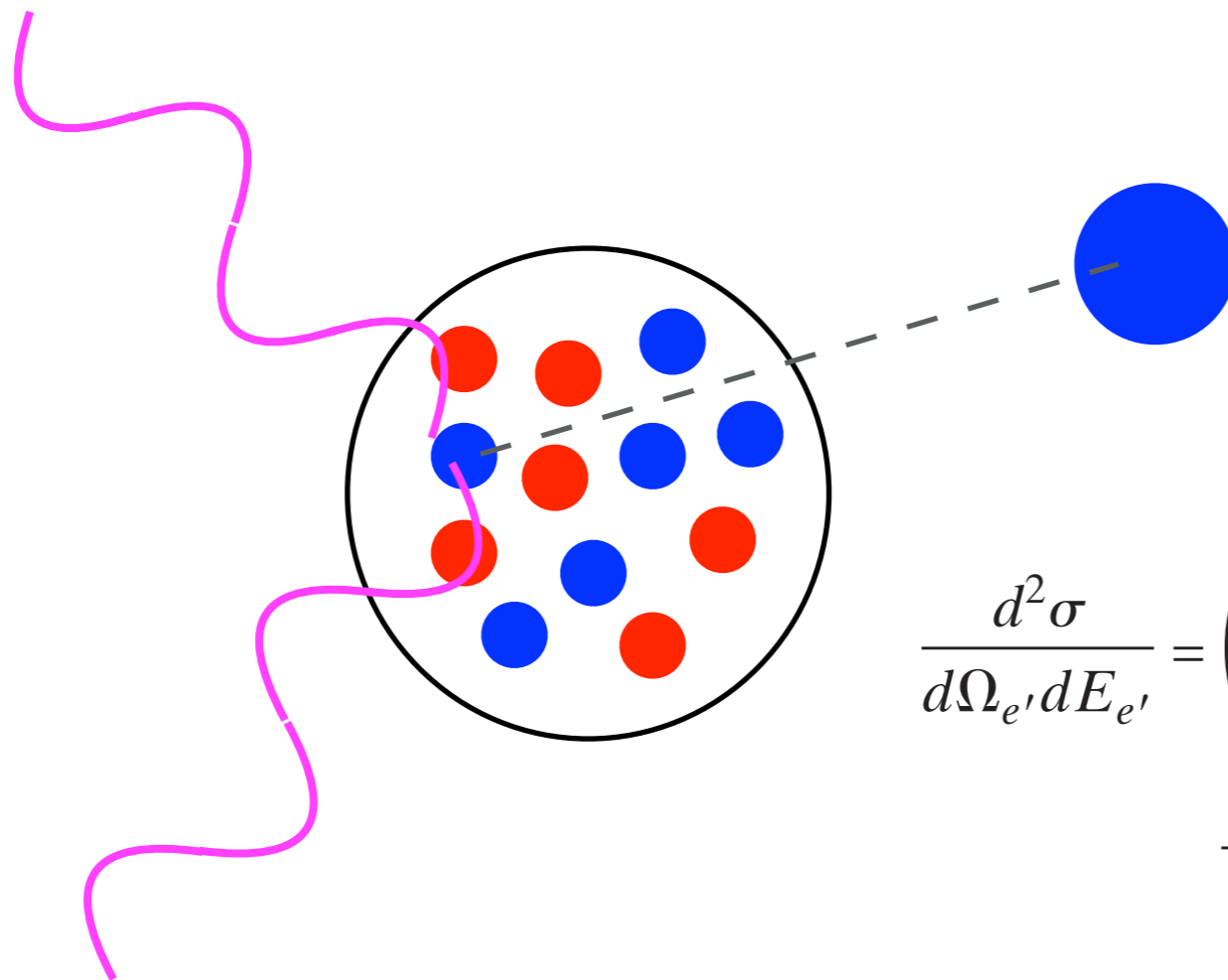

Accelerator Neutrino Experiments

Quasi-Elastic scattering
At higher energies resonance and deep inelastic dominate

Why study electron scattering?
not to determine properties of electron or photon

Quasi-elastic scattering: higher q, E

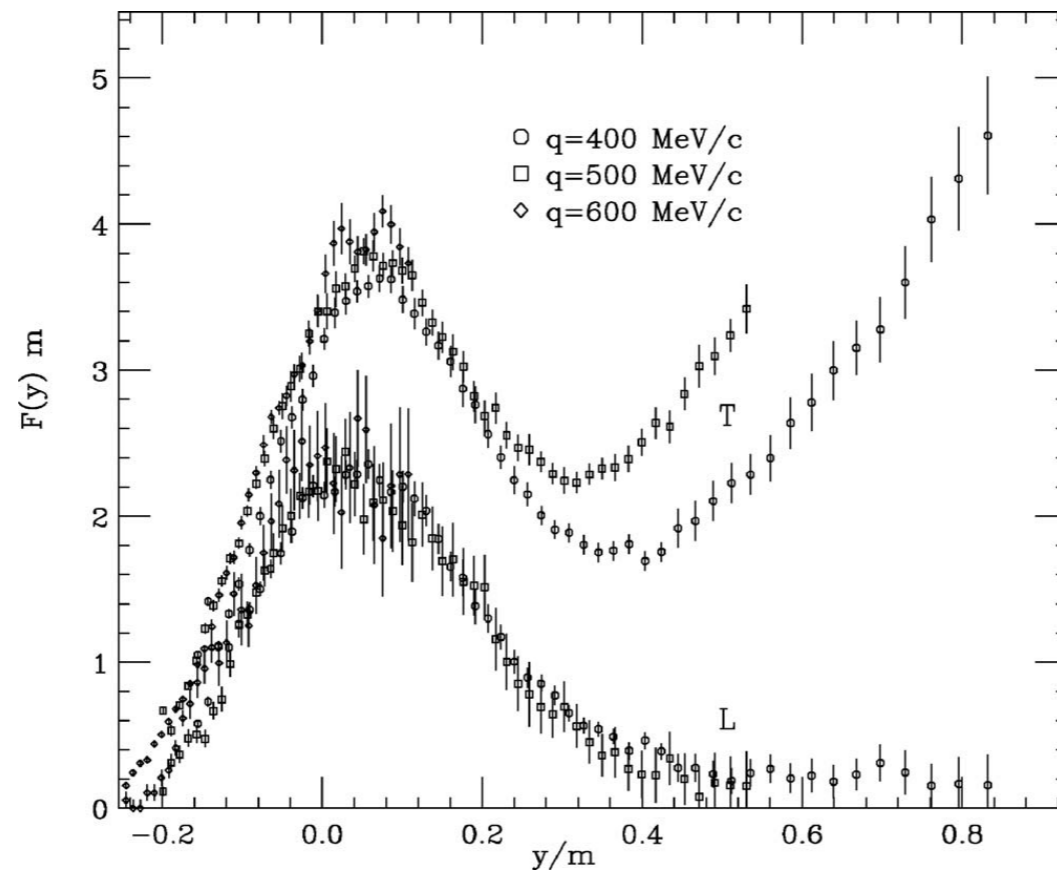Scaling with momentum transfer: 'y'-scaling
incoherent sum over scattering from single nucleons
- scaling of 1st kind-

$$\frac{d^2\sigma}{d\Omega_{e'}dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4} R_L(|\mathbf{q}|,\omega) \right.$$

$$\left. + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega) \right]$$
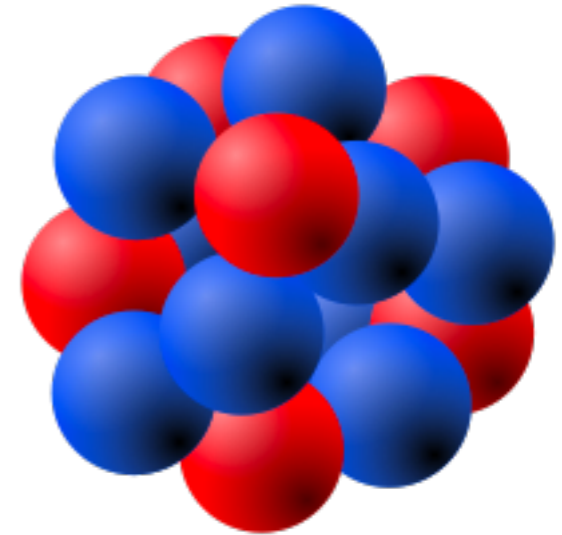
Electron Scattering: Longitudinal vs. Transverse
Single Nucleon form factors (squared) divided out

from Benhar, Day, Sick,
RMP 2008
data Finn, et al 1984

Scaled longitudinal vs.
transverse scattering from ^{12}C

Distances probed at various q

q	$r \sim \pi/q$	
0.3 GeV/c	2.1	fm
0.5 GeV/c	1.2	fm
1 GeV/c	0.6	fm

Nearest neighbor nucleons at
$\rho = 0.16 \text{ fm}^{-1} = 1 / (4/3 \; \pi \; r^3)$
r = 1.14 fm
d = 2.28 fm

Basic building blocks: Nuclear interactions and currents

NN interactions

LO ($\nu = 0$) NLO ($\nu = 2$) NNLO ($\nu = 3$)
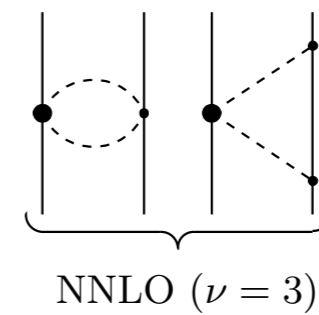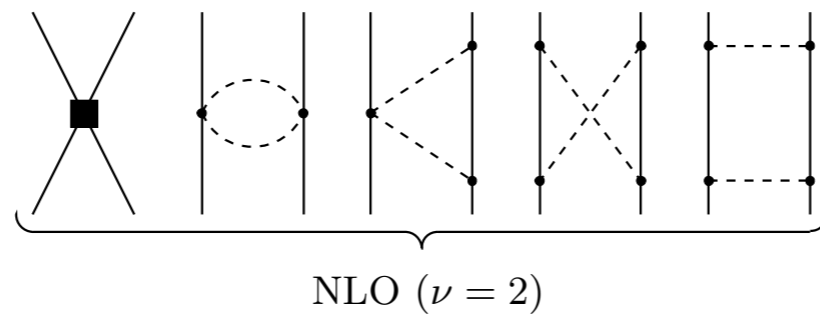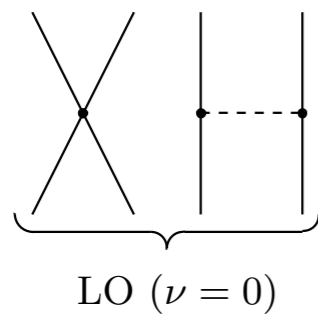
3N interactions
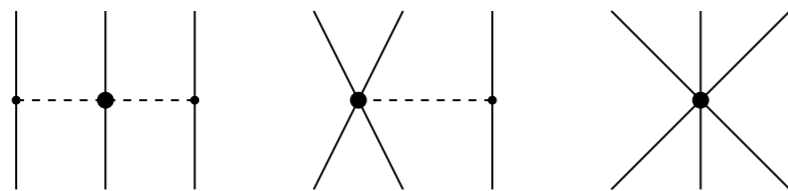
NN currents

Weak Currents

N3LO (a) (b)

N4LO (c) (d) (e)

(f) (g) (h) (i)
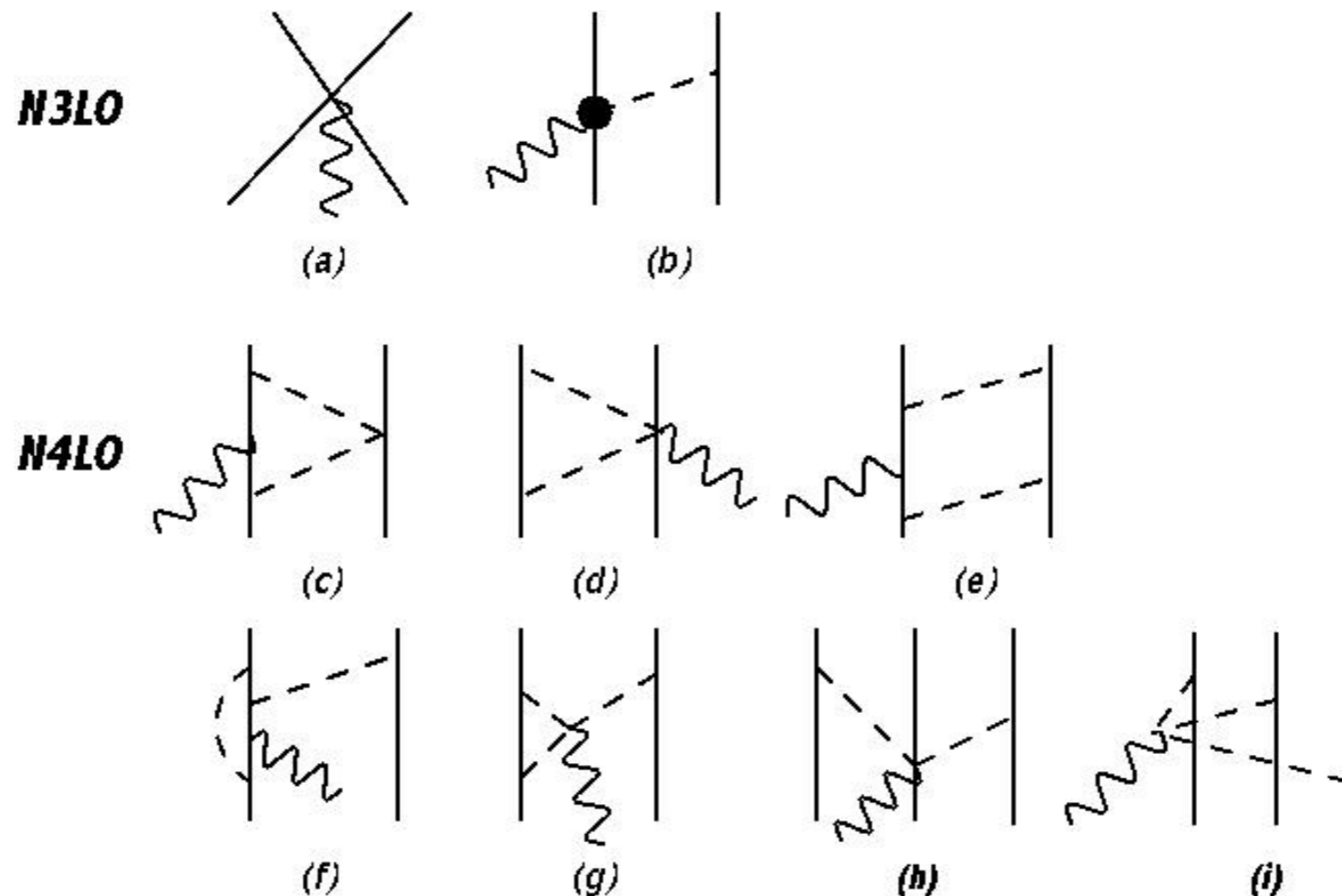
Single Nucleon Currents encoded in Form Factors
from Lattice QCD and/or experiment
Two-Nucleon Currents in NN matrix elements

Vector and Axial currents: beta decay
5 response functions in inclusive neutrino scattering

Beta Decay in Light Nuclei

Pastore, et al, 2017
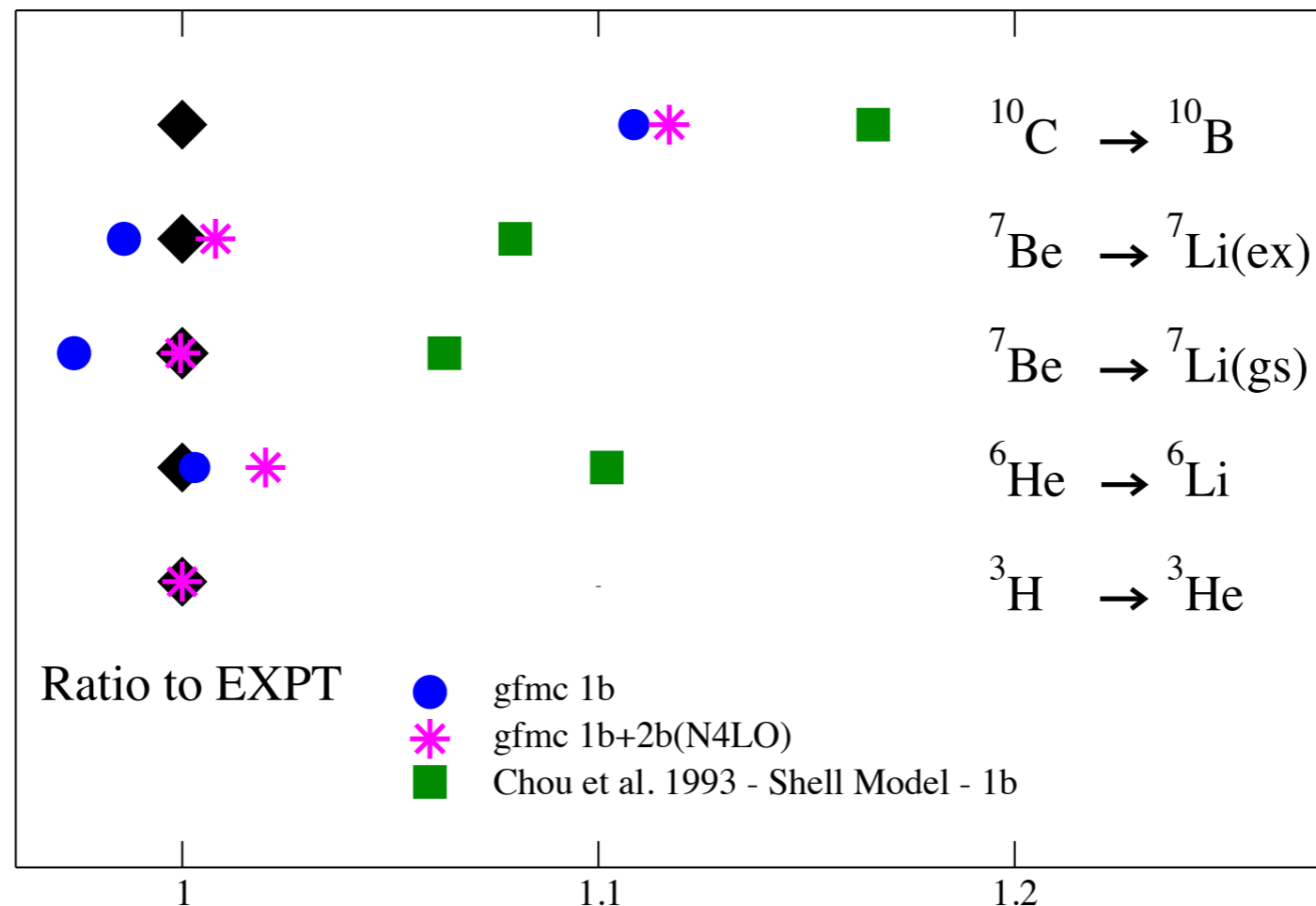
- Contact fit to Tritium beta decay
- Substantial reduction due to two-body correlations
- Modest 2N current contribution
- Good description of experimental data, explains 'quenching'
- Many calculations with larger nuclei underway

Quasi-Elastic Scattering and Plane Wave Impulse Approximation
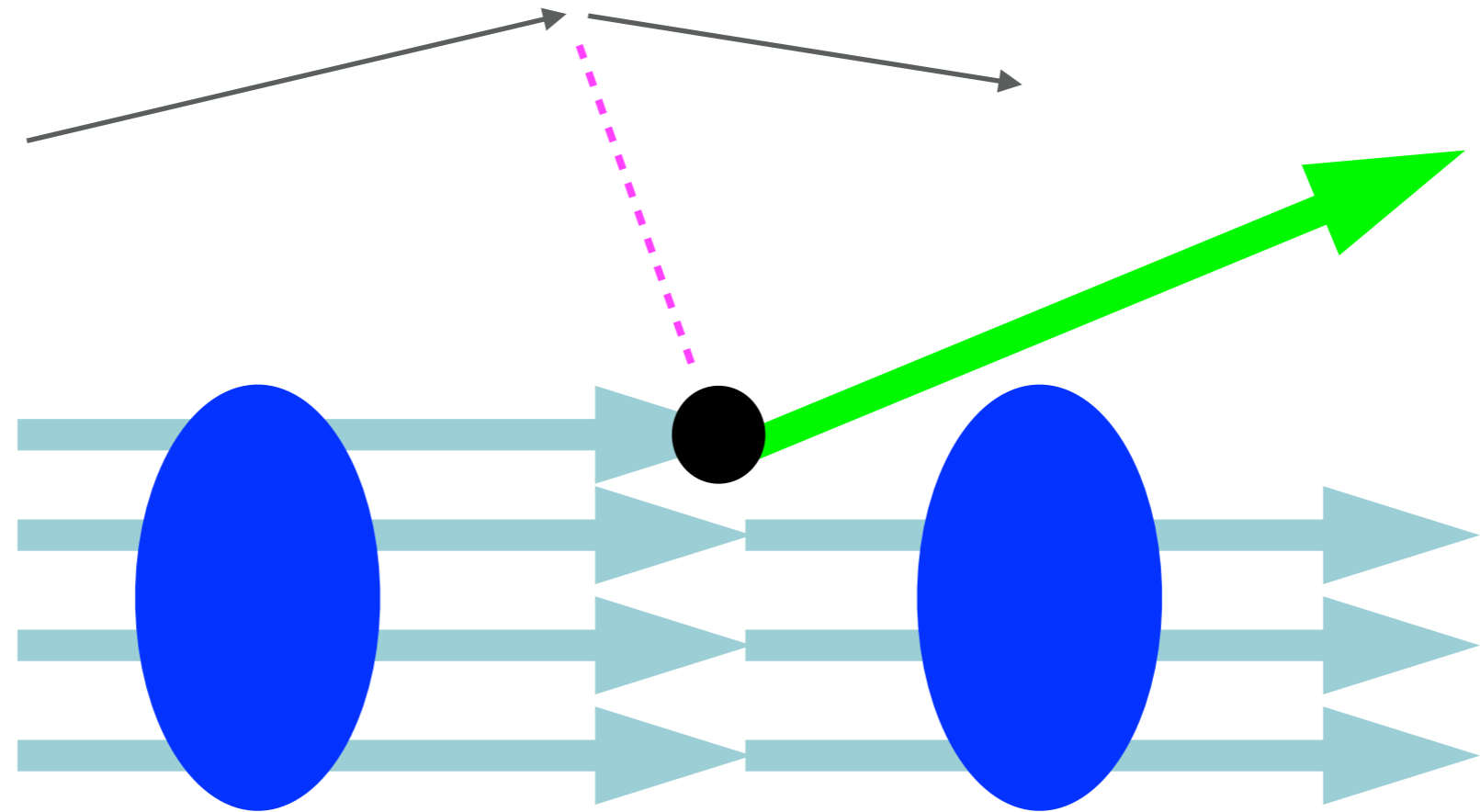
Incorporates incoherent scattering of single nucleons:
n(k) or spectral function S(k,w)
and single-nucleon form factors

Single-Nucleon Momentum Distributions

Preliminary

Chiral interactions

Different Nuclei
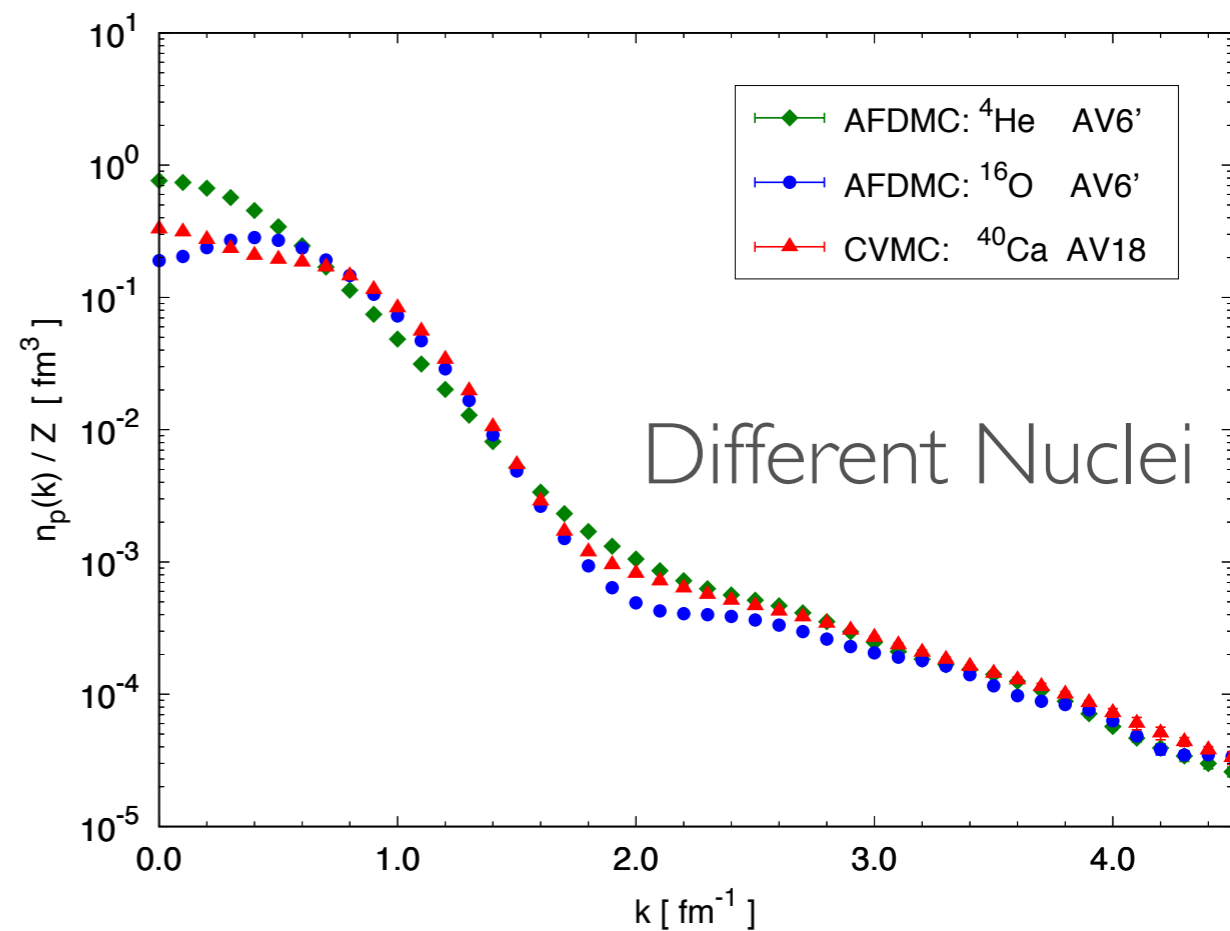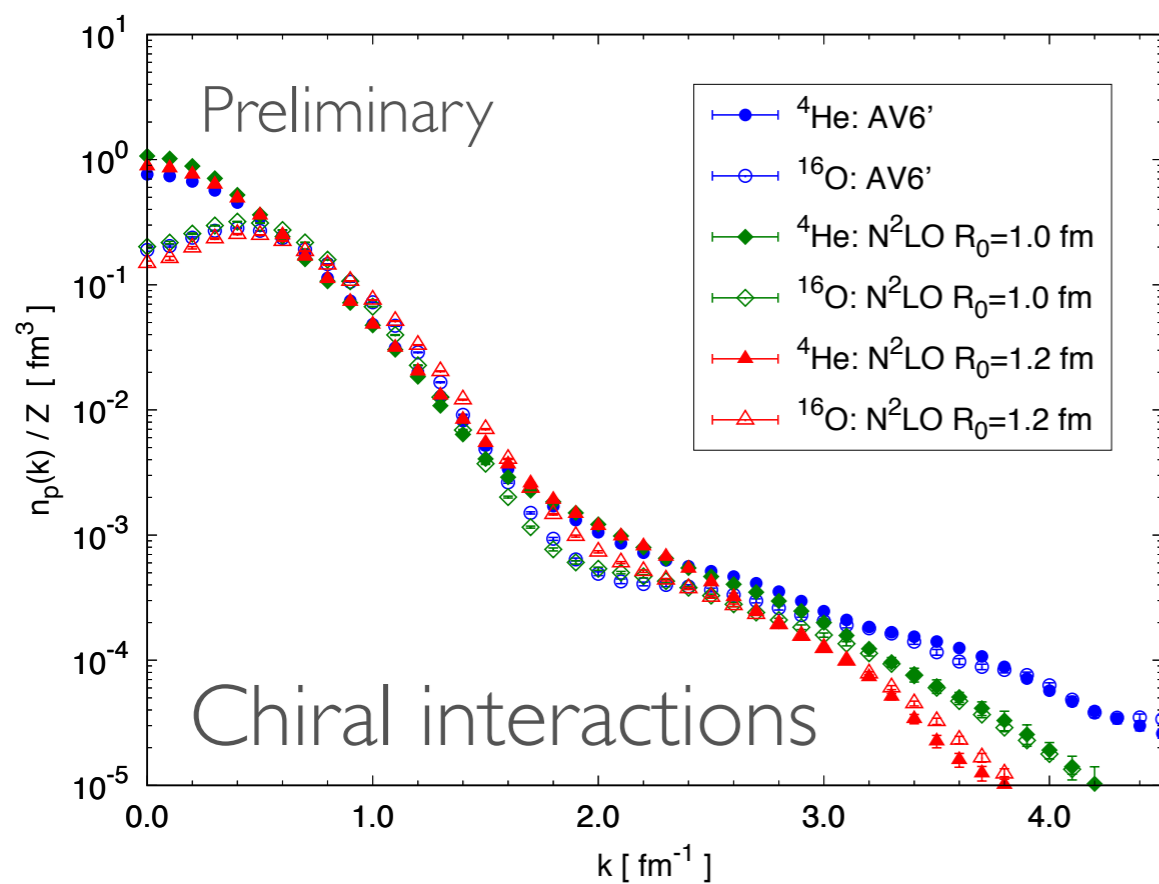
Lonardoni, Gandolfi, Wiringa, Pieper, et al

Integrated Strength:
15-20 % above k_F,
Amplitude ~ 0.3-0.4

Scaling of the 1st kind (w/ p)
Donnelly & Sick (1999)
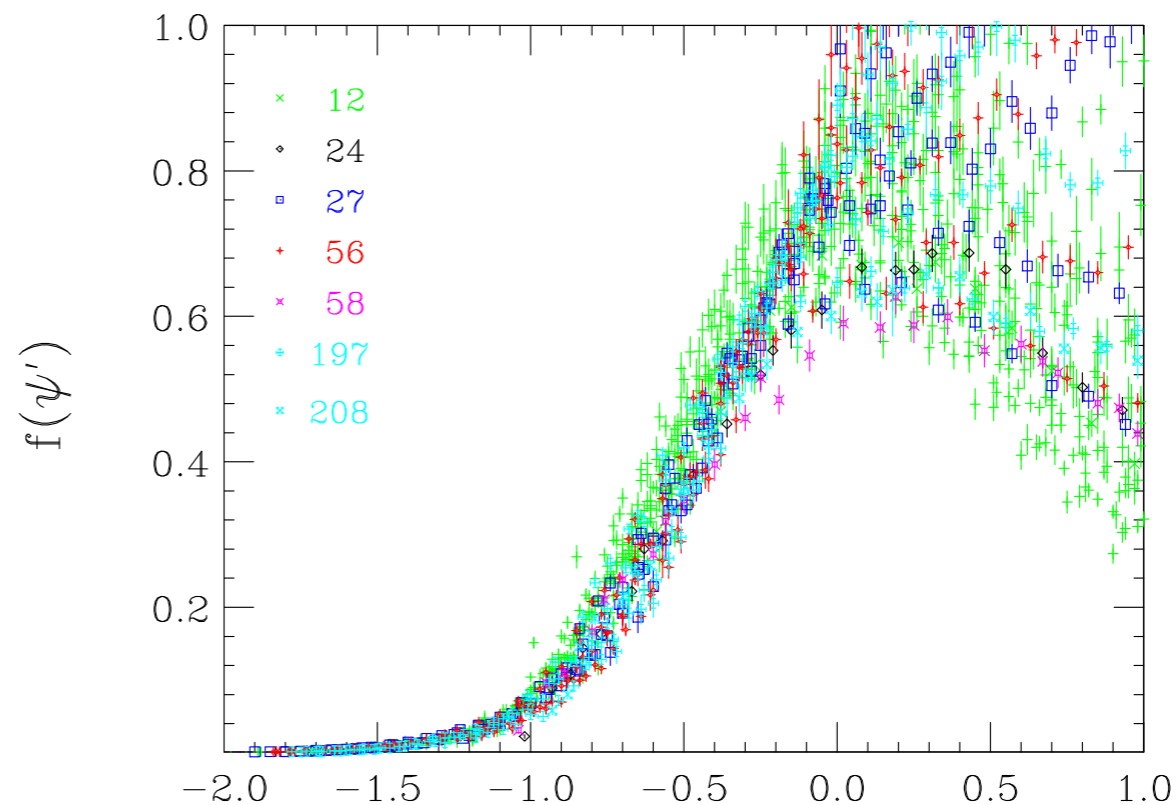
Back to Back Nucleons (total Q~0)
np pairs dominate over nn and pp
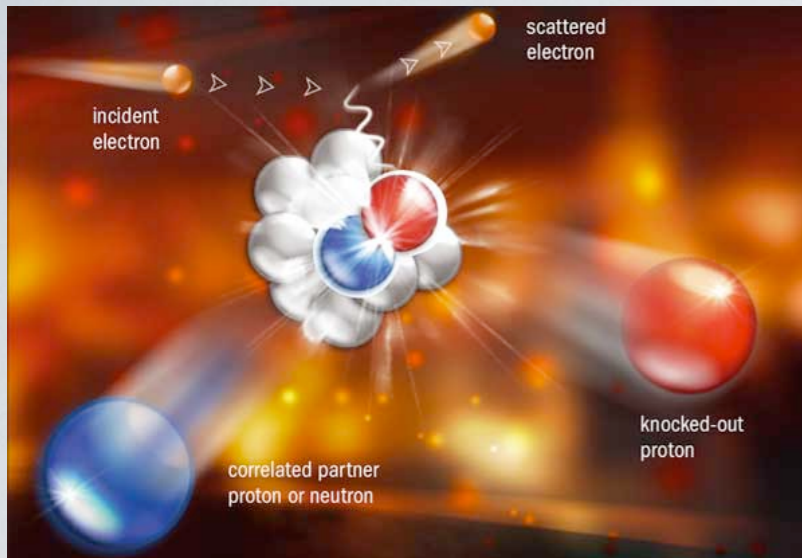
E Piasetzky *et al.* 2006 **Phys. Rev. Lett. 97** 162504.
M Sargsian *et al.* 2005 **Phys. Rev. C 71** 044615.
R Schiavilla *et al.* 2007 **Phys. Rev. Lett. 98** 132501.
R Subedi *et al.* 2008 **Science 320** 1475.

2-nucleon momentum distributions

^{16}O

pn: Eτ R_0=1.0fm
pp: Eτ R_0=1.0fm
pn: E1 R_0=1.2fm
pp: E1 R_0=1.2fm

$\rho_{pN}(q, Q=0)$ (fm^3)

q (fm^{-1})

^{12}C
^{10}B
^{8}Be
^{6}Li
^{4}He

$\rho_{pN}(q,Q=0)$ (fm^3)

q (fm^{-1})
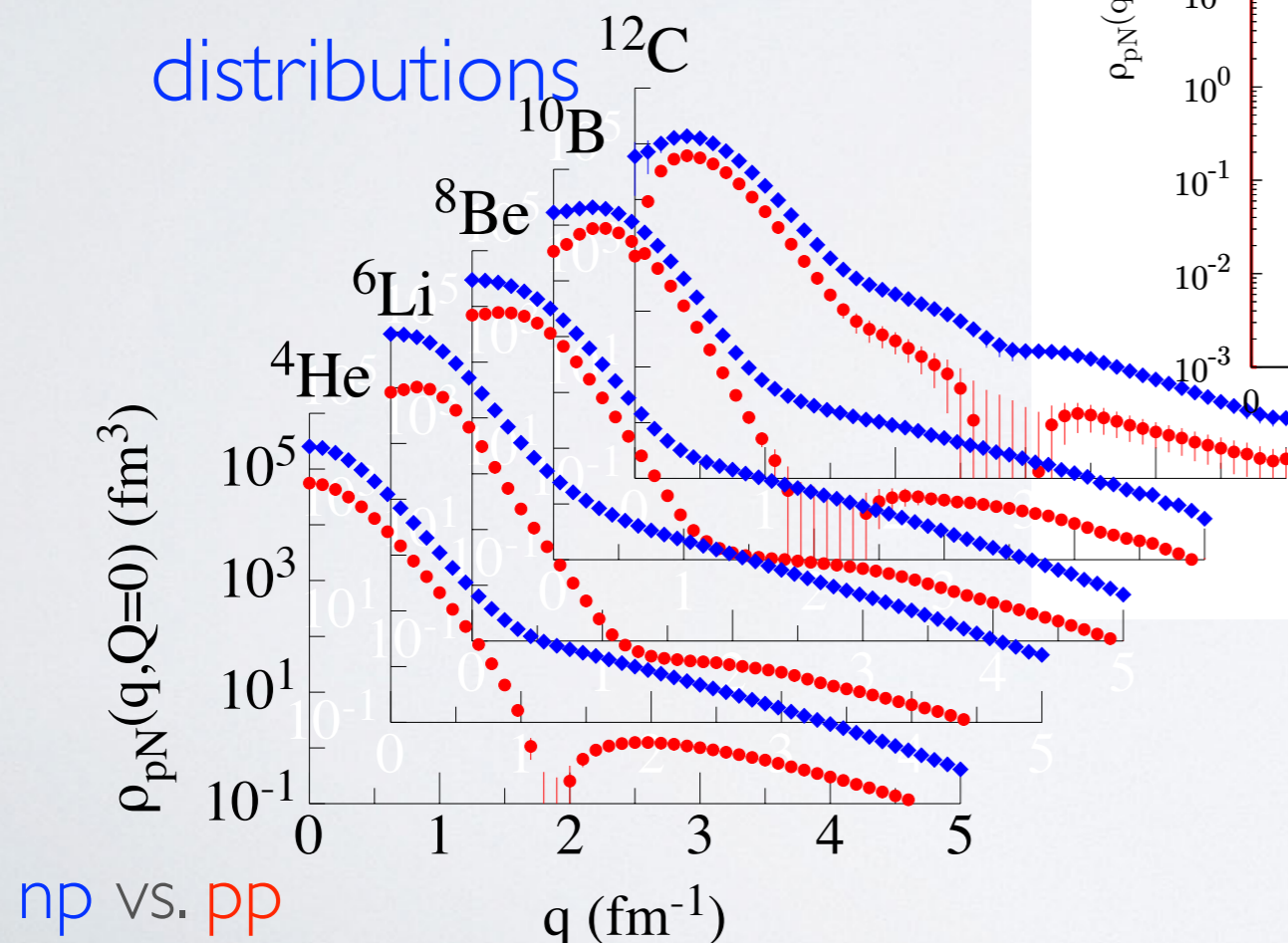
np vs. pp

Wiringa et al.; Carlson, et al, RMP 2015
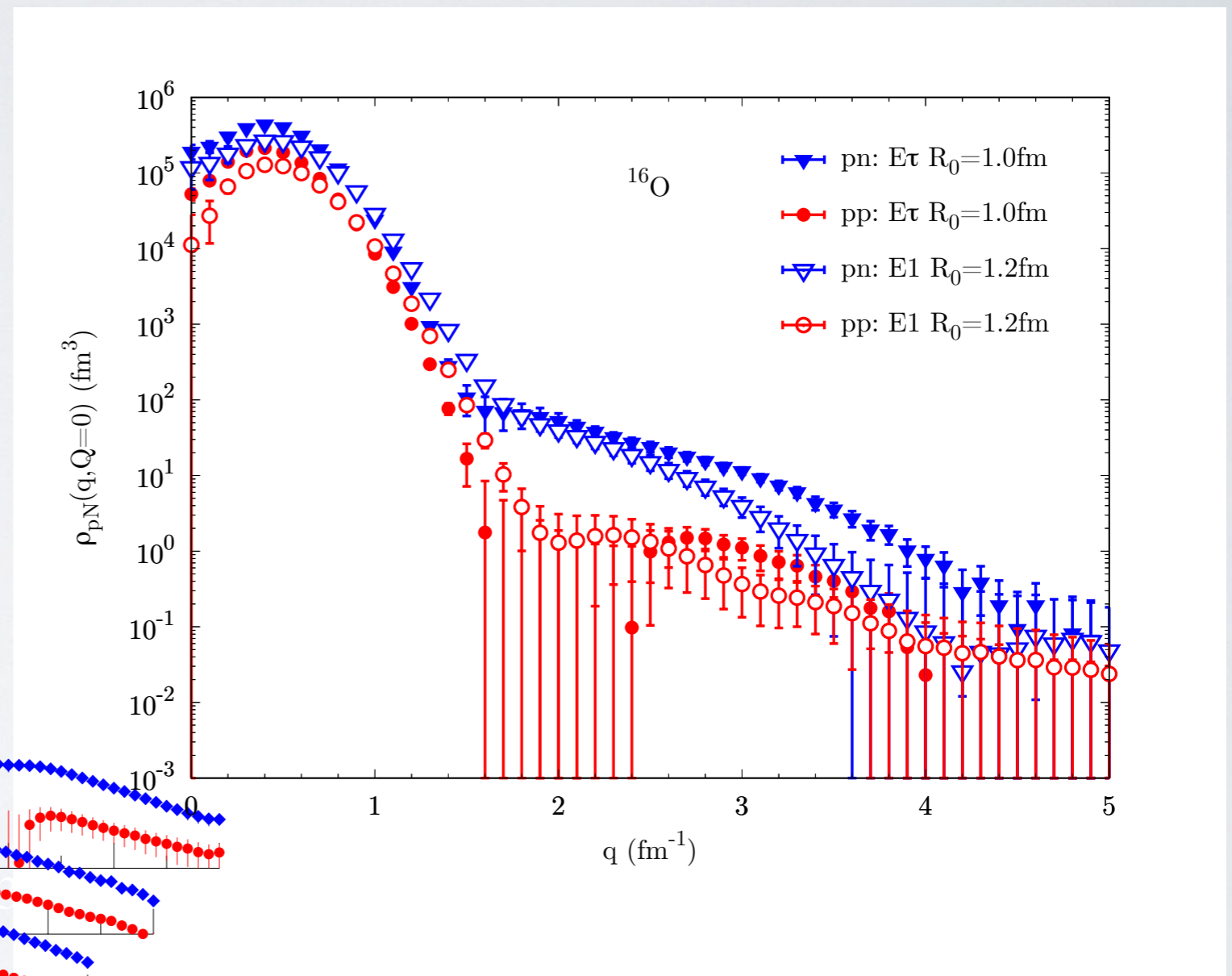
see talk of Bob Wiringa
also work of Diego Lonardoni

Electron Scattering:
Longitudinal and Transverse Response

Transverse (current) response:
$$R_T(q,\omega) = \sum_f \langle 0| \, \mathbf{j}^\dagger(q) \, |f\rangle\langle f| \, \mathbf{j}(q) \, |0\rangle \, \delta(w - (E_f - E_0))$$

Longitudinal (charge) response:
$$R_L(q,\omega) = \sum_f \langle 0| \, \rho^\dagger(q) \, |f\rangle\langle f| \, \rho(q) \, |0\rangle \, \delta(w - (E_f - E_0))$$

$$\mathbf{j} = \sum_i \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + ...$$
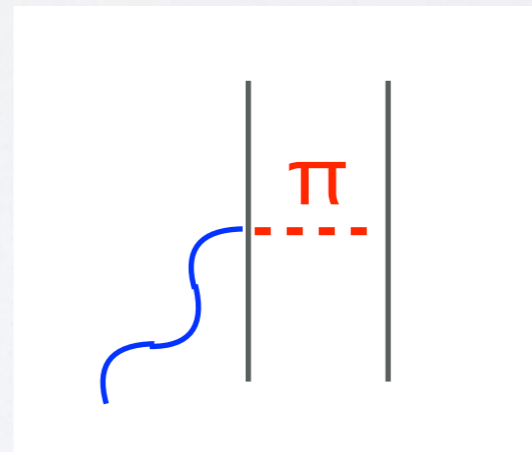
Two-nucleon currents required by current conservation
Response depends upon all the excited states of the nucleus

Sum rules in ^{12}C: neutral current scattering

Longitudinal

Transverse

EM
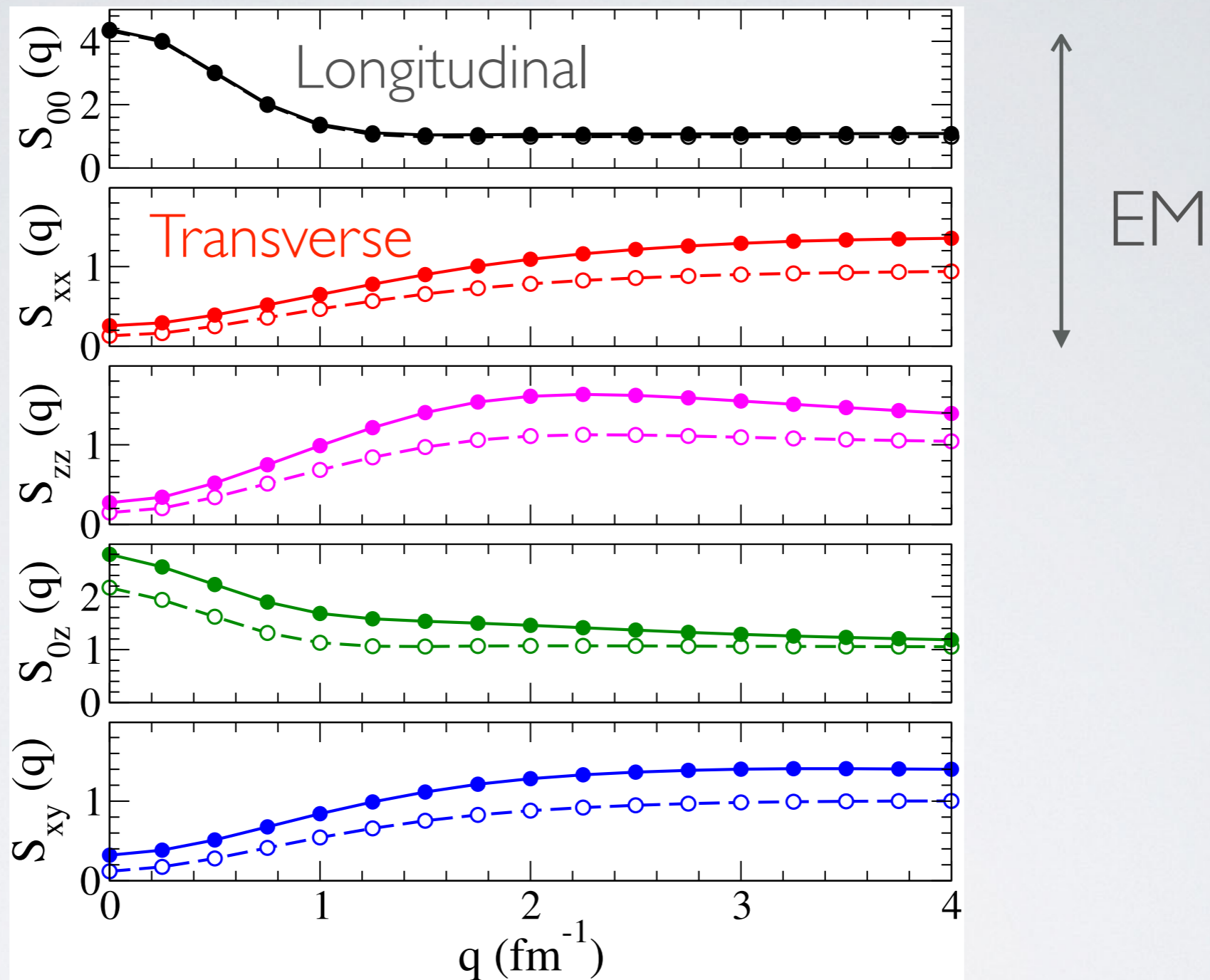
Lovato, et. al PRL 2014

Single Nucleon currents (open symbols) versus
Full currents (filled symbols)

Sum Rule: Longitudinal Response

$$S(q) = \langle 0 | \mathbf{j}^\dagger(q)\, \mathbf{j}(q)\, 0 \rangle$$

Gives an indication of total strength, but not energy dependence

Energy dependence
pion exchange
final state interaction

PWIA

Sum Rule
determined by
pp correlations

p

final states

p+**q**

p

final states

p

p+**q**

p

p+**q -**

π

k

p+

p
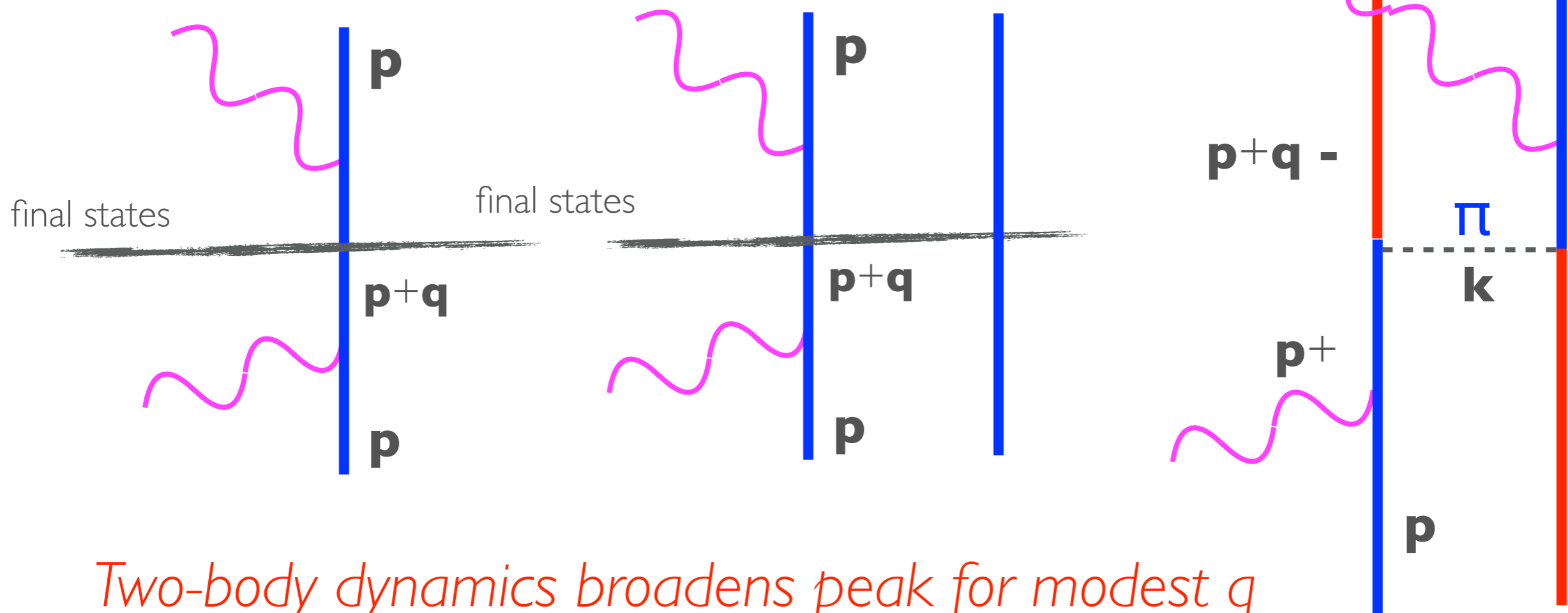
Two-body dynamics broadens peak for modest q

Vector Response

Sum Rule: Constructive Interference
between 1- and 2-body currents
w/ tensor correlations

PWIA

final state

p

p+q

p+q -

p

p

k

p

p

π

k

p

p' +

p+q - k

p'

p

k

p' + k

k

π

p'

Large enhancement from
combination of initial state correlations
and two-nucleon currents
similar in axial response
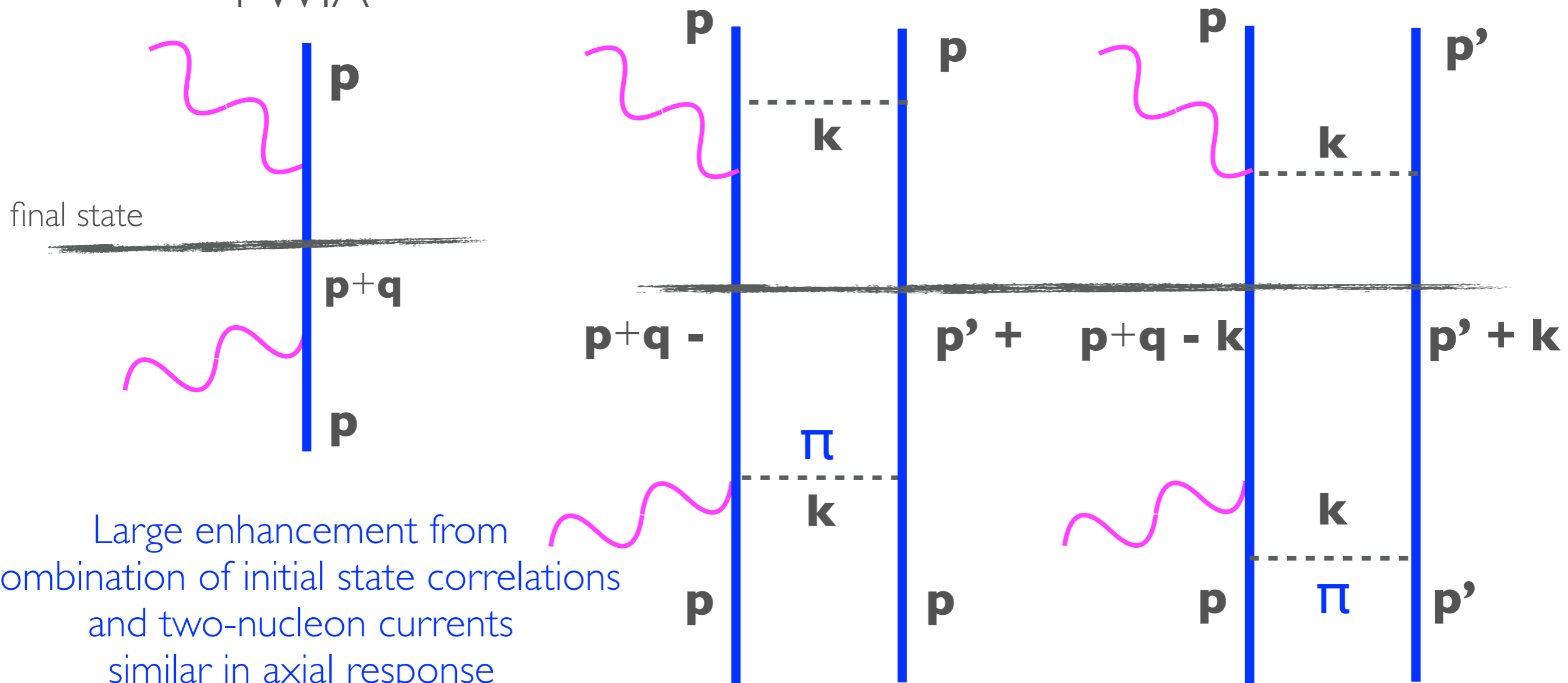
Note enhancement from
final states have larger momenta

$$\propto \ \sigma_i \cdot \mathbf{k} \ \sigma_i \cdot \mathbf{q} \ (\sigma_j \cdot \mathbf{k})^2 \ (\tau_i \cdot \tau_j)^2 \ v_\pi^2(k)$$

Euclidean Response

Want to calculate

$$R(q, \omega) = \int dt \, \langle 0 | \, \mathbf{j}^\dagger \exp[i(H - \omega)t] \, \mathbf{j} \, |0\rangle$$

Can calculate

$$\tilde{R}(q, \tau) = \langle 0 | \, \mathbf{j}^\dagger \, \exp[-(\mathbf{H} - \mathbf{E_0} - \mathbf{q^2}/(\mathbf{2m}))\tau] \, \mathbf{j} \, |0\rangle >$$

- Exact given a model of interactions, currents
- `Thermal' statistical average
- *Full final-state interactions*
- *All contributions included - elastic, low-lying states, quasi elastic, …*

Excellent agreement
  w/ EM (L & T)
response in A=4,12
Lovato, 2015, PRL 2016
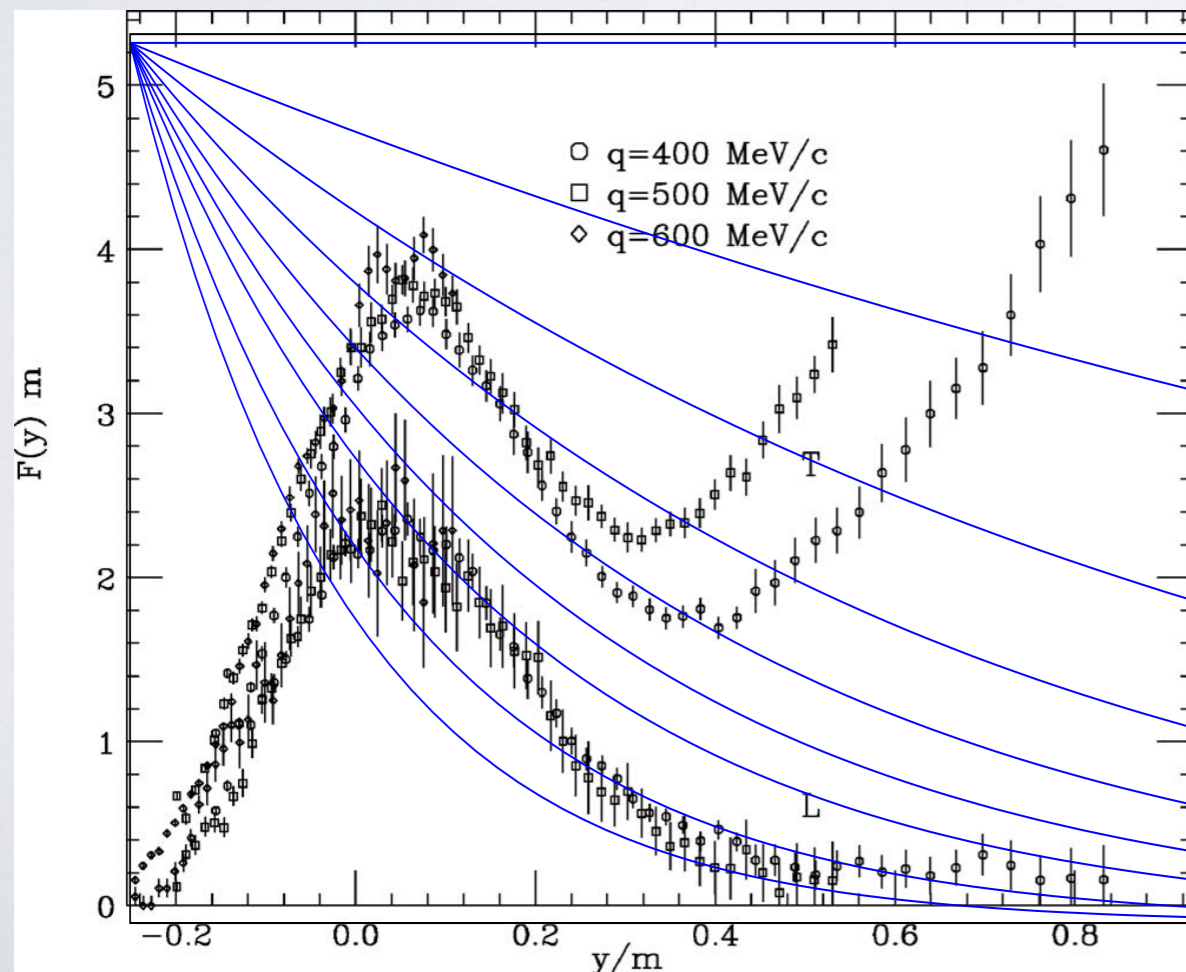
see talk of Alessandro Lovato

τ

Sum rule ➔ elastic FF^2 w/ increasing

Electron Scattering from ^{12}C: Longitudinal Response
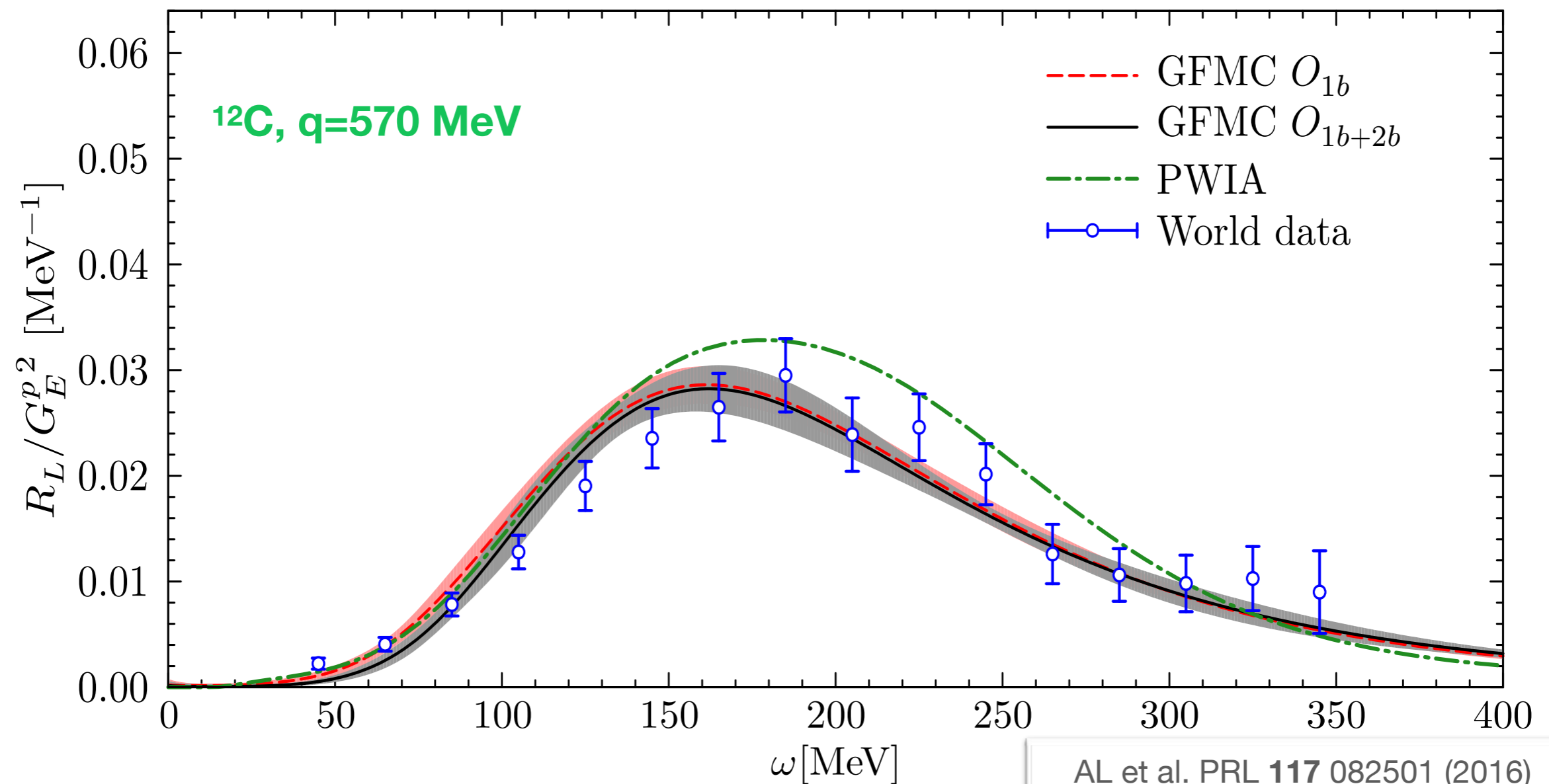
- We inverted the electromagnetic Euclidean response of ^{12}C

- Good agreement with data without in-medium modifications of the nucleon form factors

- Small contribution from two-body currents.

AL et al. PRL **117** 082501 (2016)

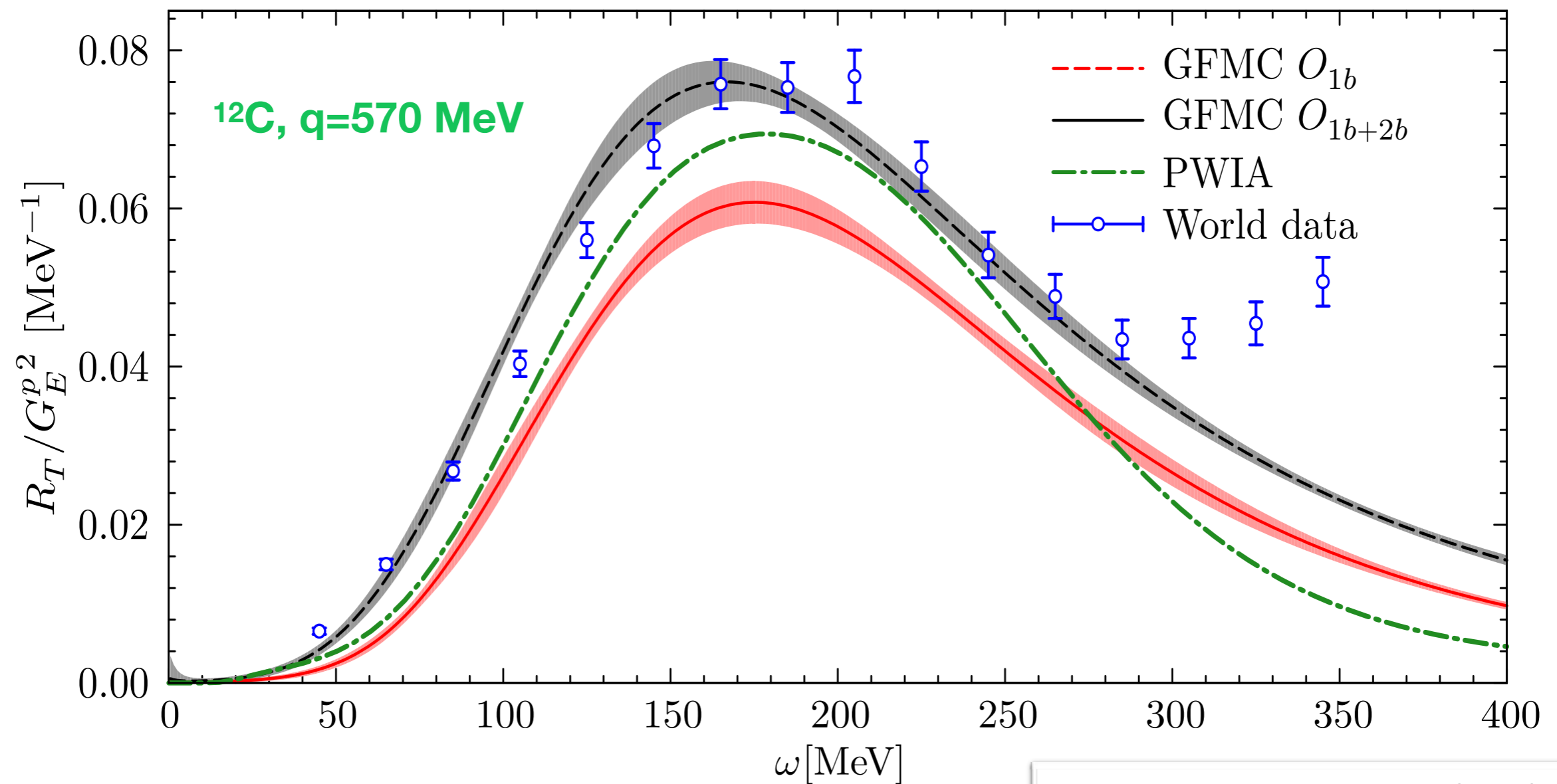# Electron Scattering from ^{12}C: Transverse Response

- We inverted the electromagnetic Euclidean response of ^{12}C

- Good agreement with the experimental data once two-body currents are accounted for

- Need to include relativistic corrections in the kinematics

AL et al. PRL **117** 082501 (2016)

^{12}C charged-current responses

- We recently computed the charged-current response function of ^{12}C

- Two-body currents have little effect in the vector term, but enhance the axial contribution at energy larger than quasi-elastic kinematics
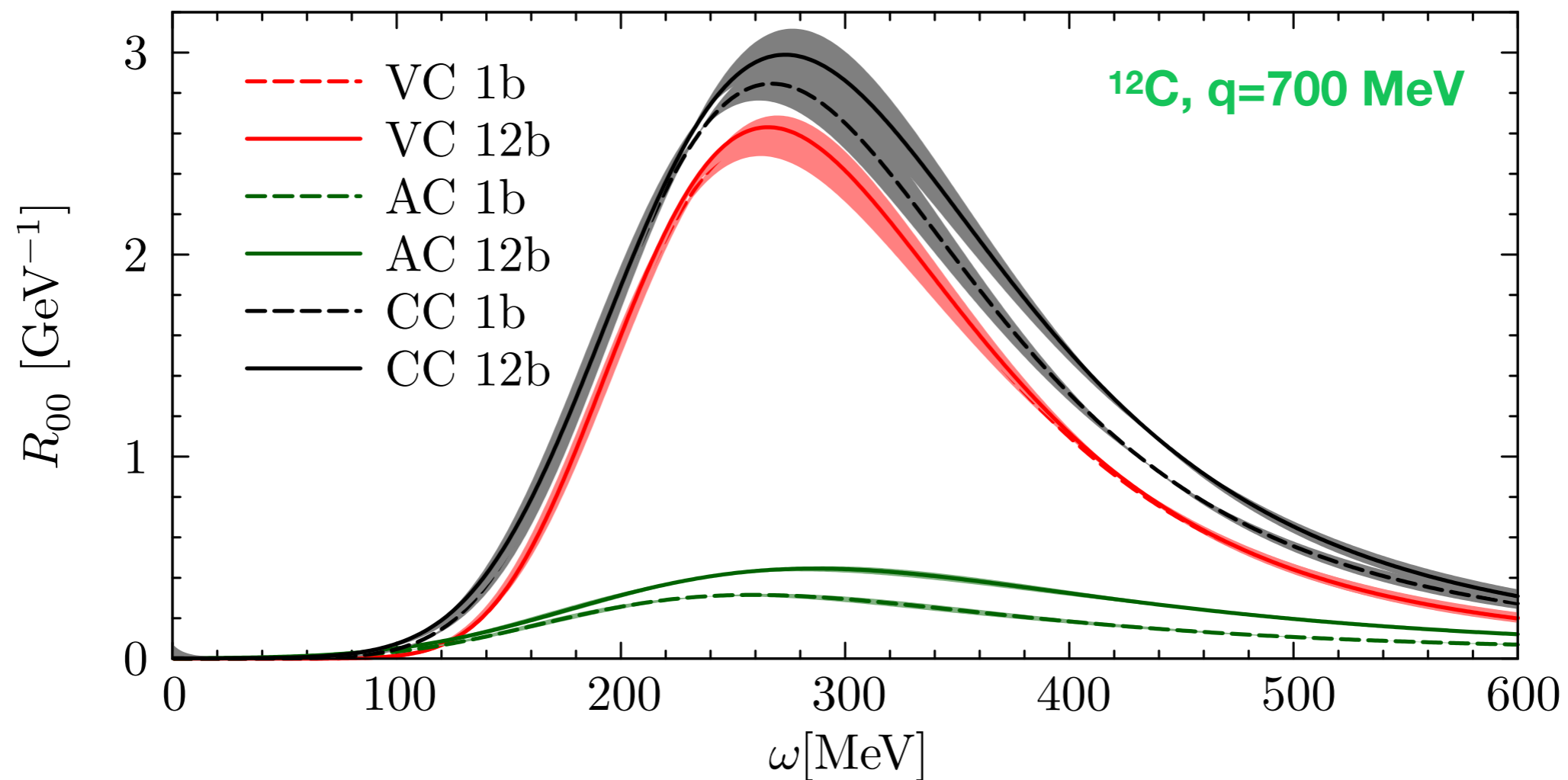
Alessandro Lovato, 2019

^{12}C charged-current responses

- We recently computed the charged-current response function of ^{12}C
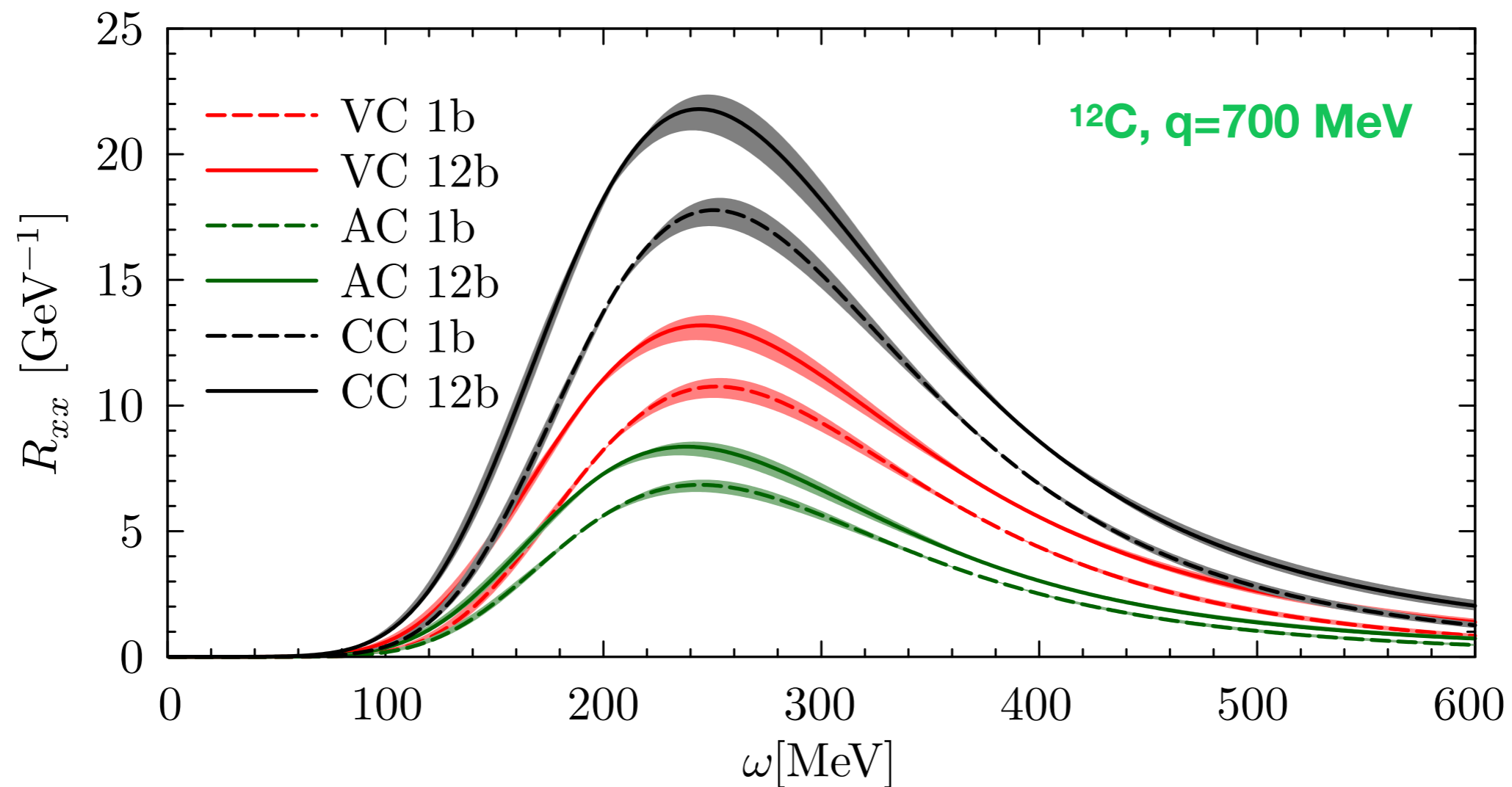
- Two-body currents have a sizable effect in the transverse response, both in the vector and in the axial contributions

Alessandro Lovato, 2019

Towards real-time dynamics: Short-time approximation

Saori Pastore, et al, 2019

$$R^O(q, \omega) = \frac{\int d\Omega_q}{4\pi} \sum_f \langle \Psi_0 | \mathcal{O}^\dagger(\mathbf{q}) | \Psi_f \rangle \langle \Psi_f | \mathcal{O}(\mathbf{q}) | \Psi_0 \rangle \delta(E_f - E_0 - \omega),$$

$$R^O(q, \omega) = \frac{\int d\Omega_q}{4\pi} \int \frac{dt}{2\pi} \exp[i\omega t] \langle \Psi_0 | \mathcal{O}^\dagger(\mathbf{q}, t') \exp[-iHt] \mathcal{O}(\mathbf{q}, t=0) \Psi_0 \rangle,$$

At short time evolution can be described as a product of NN propagators

$$\langle \mathbf{R}', \sigma', \tau' | \exp[-iHt] | \mathbf{R}, \sigma, \tau \rangle \approx \langle \mathbf{R}', \sigma', \tau' | \prod_i \exp[-iH_i^0 t] \frac{\mathcal{S} \prod_{i<j} \exp[-iH_{ij}t]}{\prod_{i<j} \exp[-iH_{ij}^0 t]} | \mathbf{R}, \sigma, \tau \rangle$$

Evaluate as a sum of matrix elements of NN states embedded in the Nucleus

Incoherent sum of single nucleon currents

$$\sum_{q,Q,J,L,S,T} \langle \Psi_0 | \, \mathbf{j_i}^\dagger \, | \psi_{NN}(q, Q) \rangle \, \langle \psi_{NN}(q, Q) | \, \mathbf{j_i} \, | \Psi_0 \rangle \, \delta(E_f - E_i - \omega)$$

Interference of 1- and 2-nucleon currents

$$\sum_{q,Q,J,L,S,T} \langle \Psi_0 | \, \mathbf{j_{ij}}^\dagger \, | \psi_{NN}(q, Q) \rangle \, \langle \psi_{NN}(q, Q) | \, \mathbf{j_i} \, | \Psi_0 \rangle \, \delta(E_f - E_i - \omega)$$

Diagonal 2-nucleon currents

$$\sum_{q,Q,J,L,S,T} \langle \Psi_0 | \, \mathbf{j_{ij}}^\dagger \, | \psi_{NN}(q, Q) \rangle \, \langle \psi_{NN}(q, Q) | \, \mathbf{j_{ij}} \, | \Psi_0 \rangle \, \delta(E_f - E_i - \omega)$$

Properties of short-time approximation

- Includes incoherent scattering plus interference between single nucleon terms and interference between one- and two-nucleon currents

- Must be calculated at each q
    - Fully incorporates Pauli exclusion principle
    - Correct sum rule, good approximation to energy-weighted sum rule
    - Includes charge propagation due to pion exchange

- Gives two-nucleon information after the vertex
    - Now: relative and CM energy (or momentum) of the pair
        - separation into different kind of pairs
    - Future: angular dependence of q.P', q.p'
        - (where p',P' are the momenta of the final state pair)

- Intermediate between fully quantum evolution and single-nucleon vertex
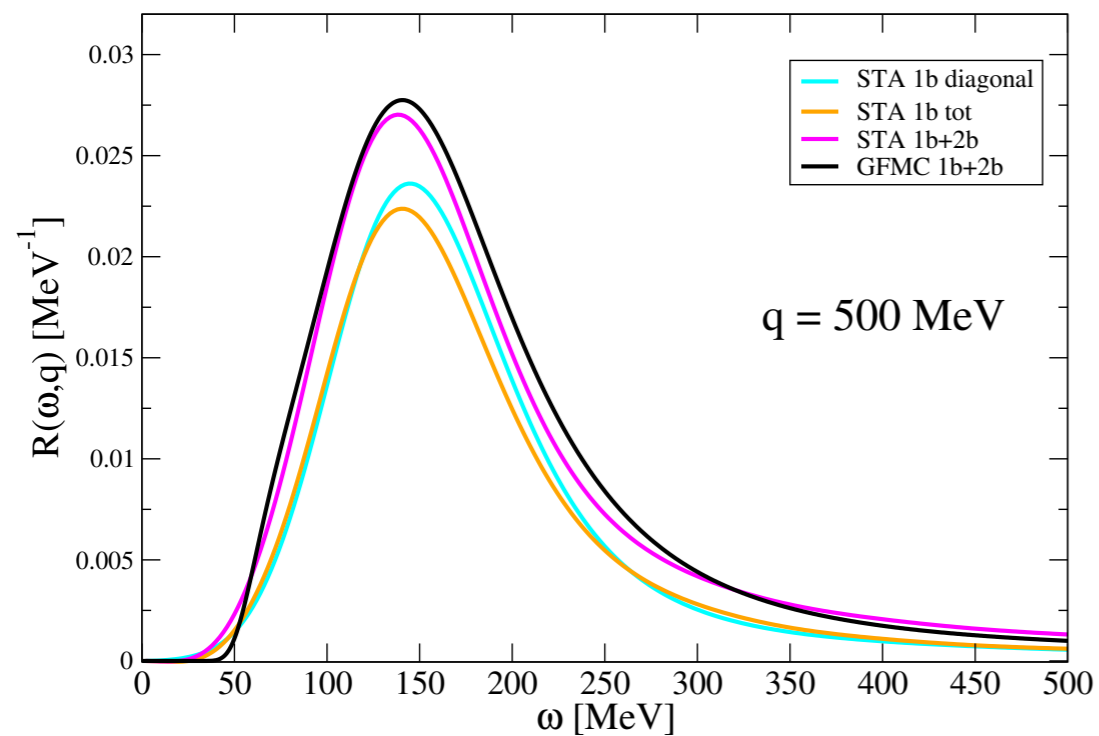   - Classical evolution of the pair interacting with other nucleons still required

Response Densities

- Integral over surfaces w/ constant e+E gives full response

Transverse Density $q = 300$ MeV
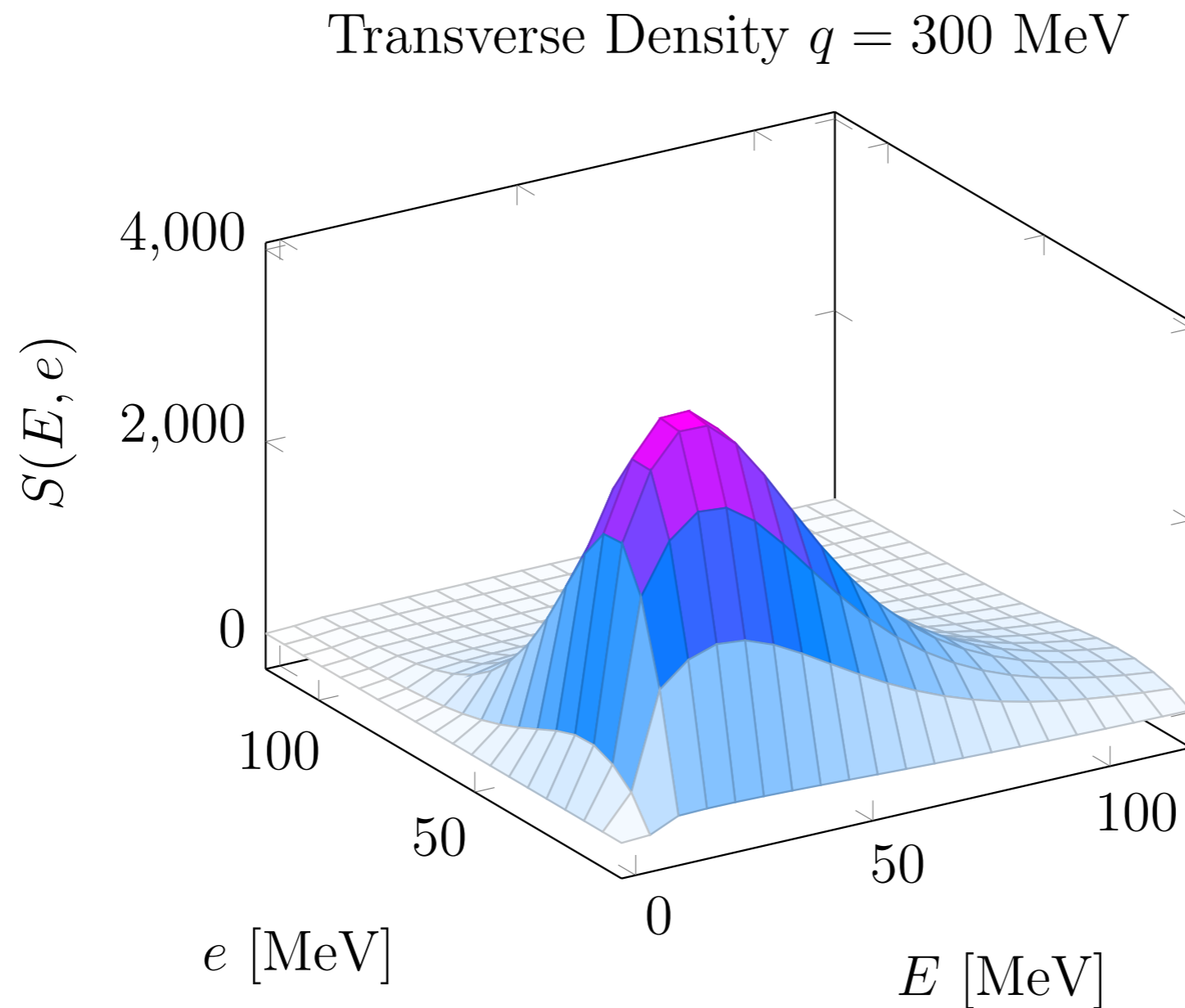
Response functions in STA vs. GFMC

^{4}He Electromagnetic Transverse Response Function
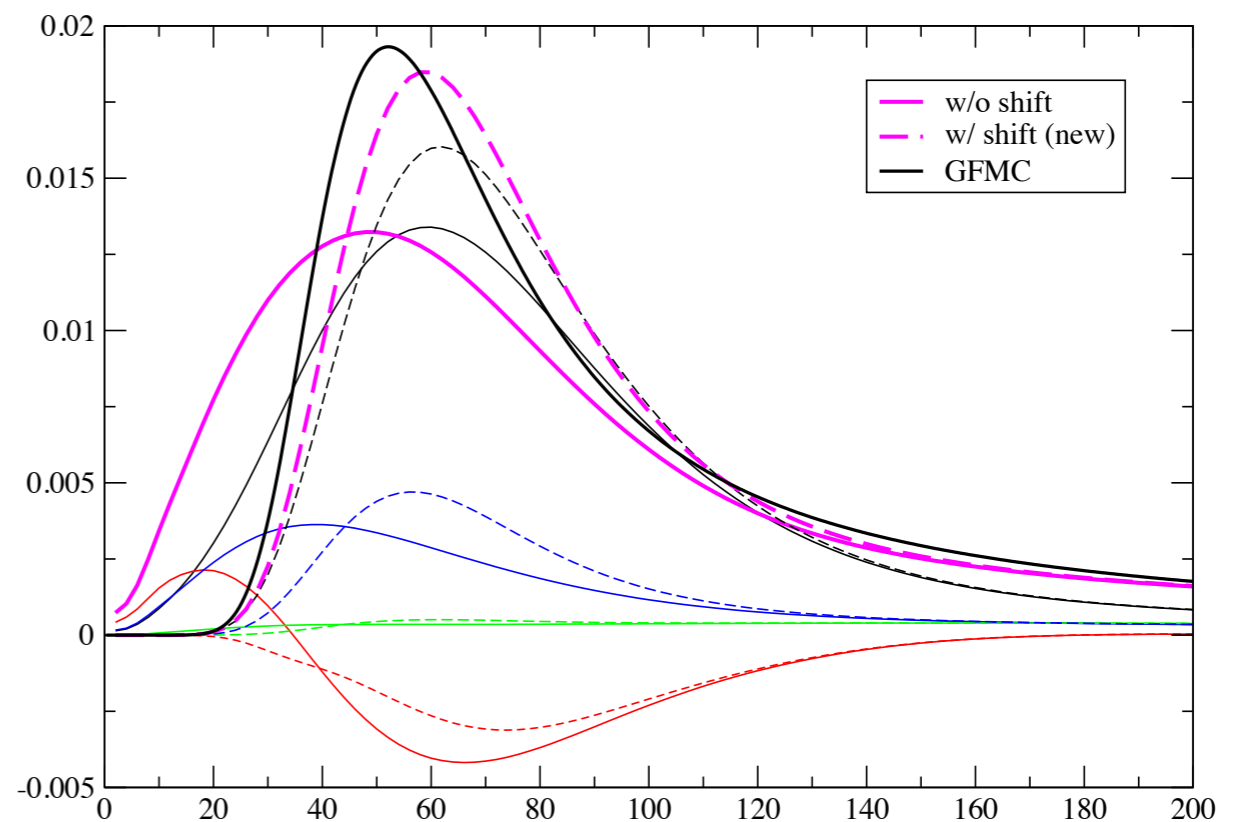
q = 500 MeV

^{4}He Electromagnetic Transverse Response Function

q=500 MeV/c
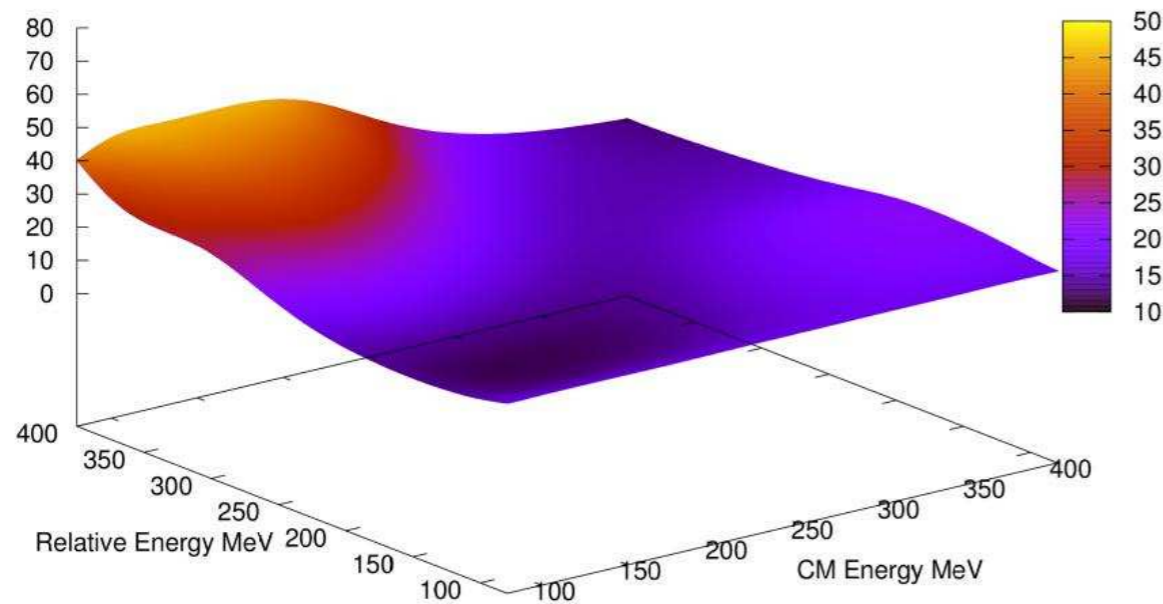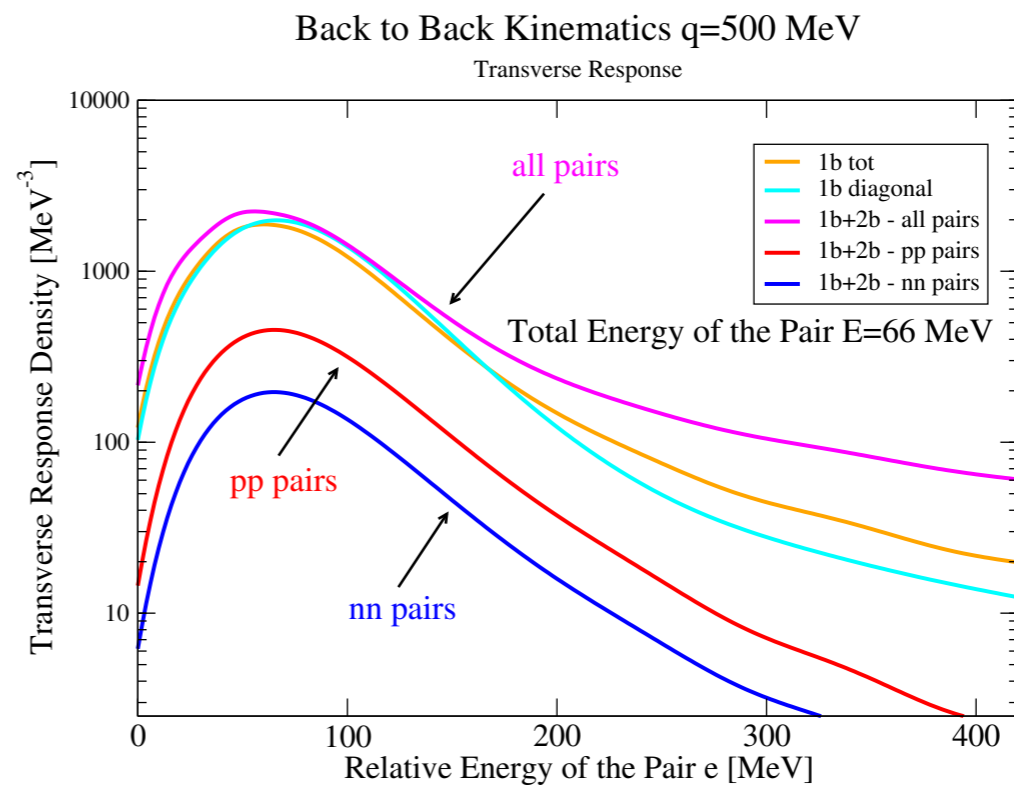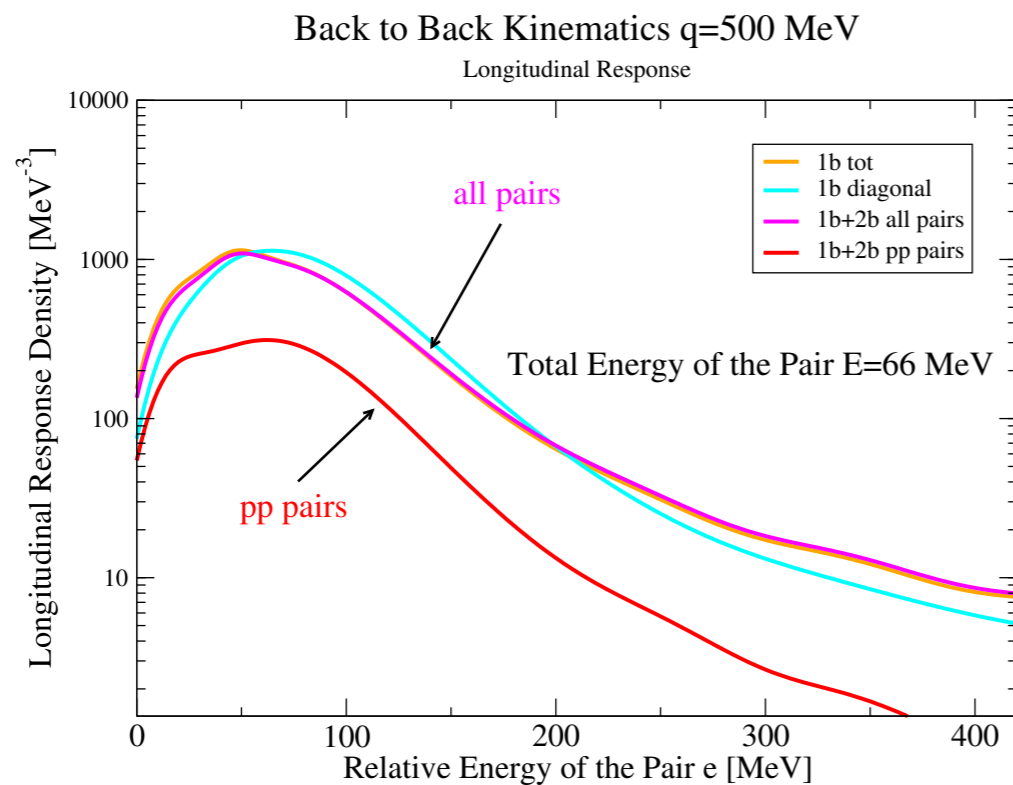
q = 500 MeV

q=300 MeV/c
using extra info about threshold
probably ~lower energy limit

Back-to-Back nucleons in STA

Average contribution
of 2N currents ~30%
Up to ~1/2 of response in
back-to-back regime

Back to Back Kinematics q=500 MeV

Longitudinal Response

- 1b tot
- 1b diagonal
- 1b+2b all pairs
- 1b+2b pp pairs

all pairs

Total Energy of the Pair E=66 MeV

pp pairs

Back to Back Kinematics q=500 MeV

Transverse Response

- 1b tot
- 1b diagonal
- 1b+2b - all pairs
- 1b+2b - pp pairs
- 1b+2b - nn pairs

all pairs

Total Energy of the Pair E=66 MeV
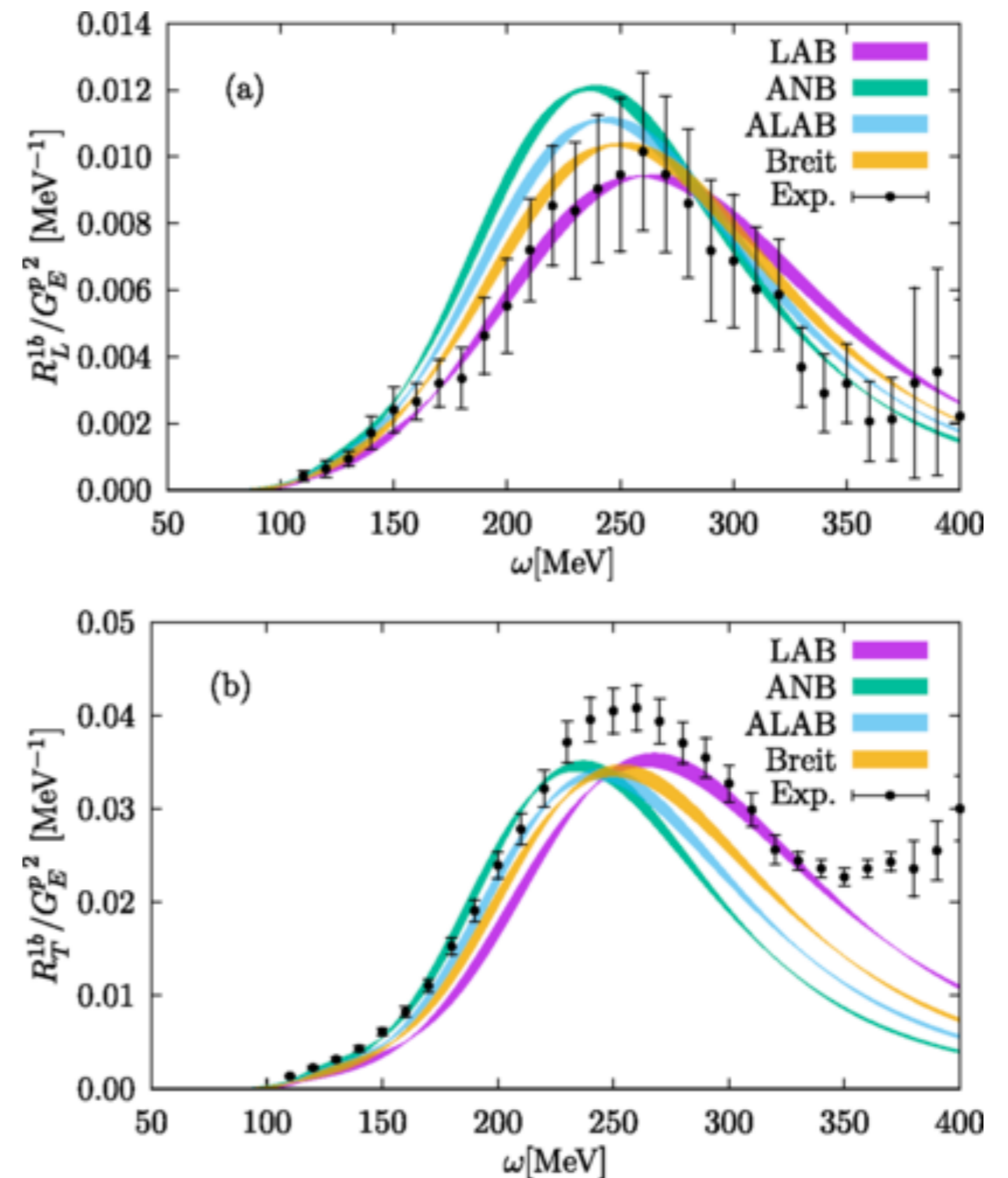
pp pairs

nn pairs

Future directions (resonance region)

- Relativistic Dynamics

- Pion Production and Deltas
  from two hadrons

  requires model of NN inelastic processes
 can we match to lattice calculations?

Noemi Rocco, et al (2018)

Quantum Computing
and Real-Time quantum dynamics
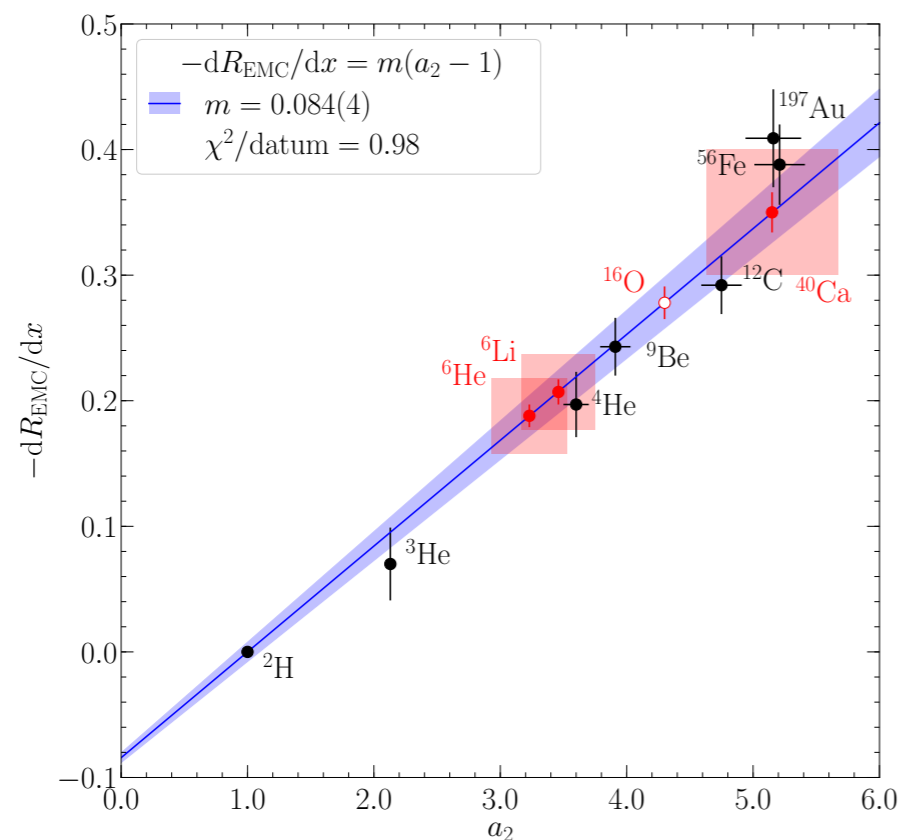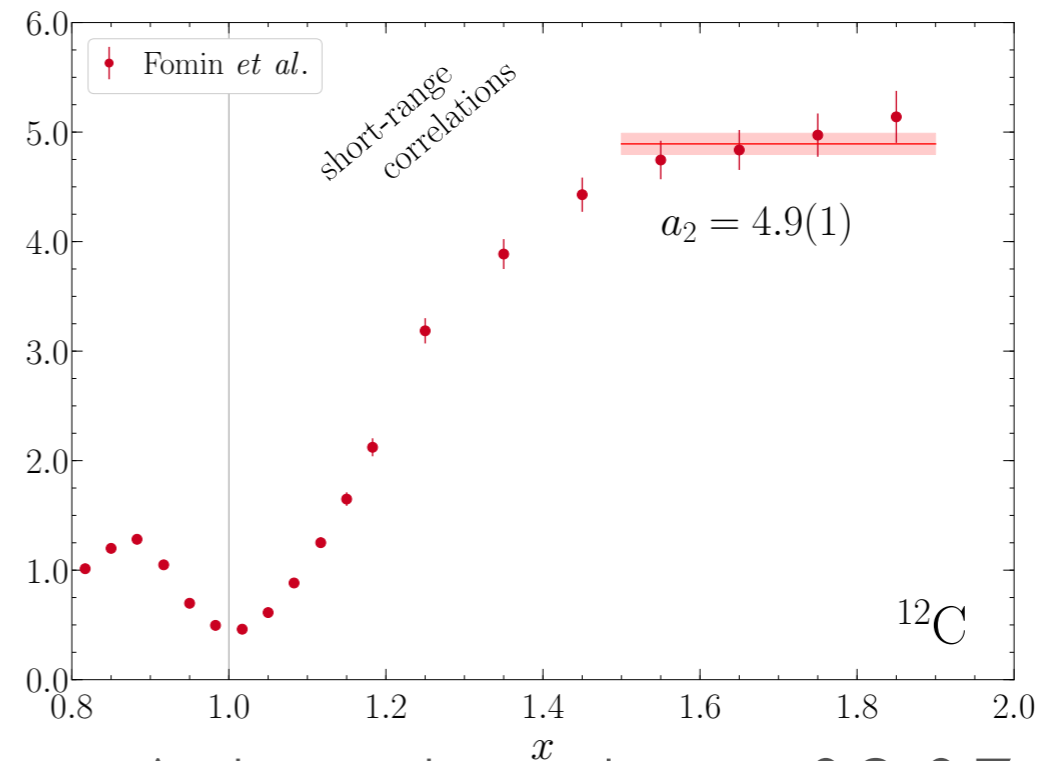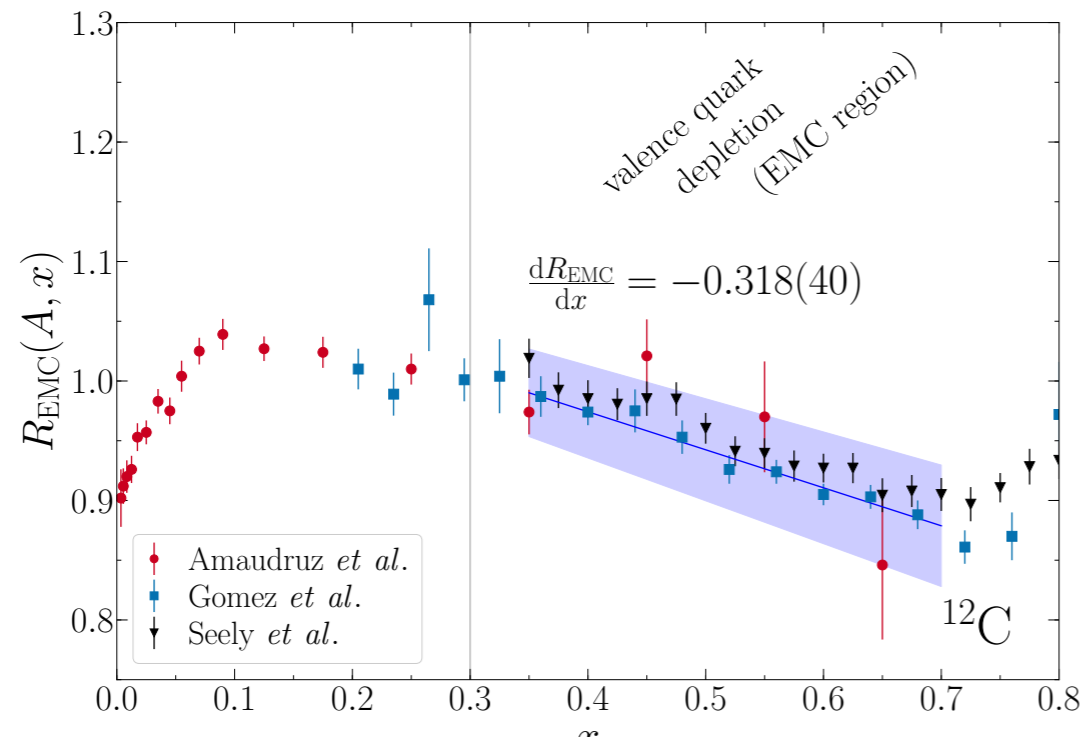### for neutrino-nucleus interactions

$$R(q, \omega) = \int dt \, \langle 0| \, \mathbf{j}^\dagger \exp[i(H - \omega)t] \, \mathbf{j} \, |0\rangle$$

- use quantum computer
- test ideas on simple problems
- gradually extend to more realistic cases

- Only fairly modest time-propagation is required
  (modest coherence time)
- Quantum vs. Classical dynamics
- Dynamics of entanglement
- Impact on specific observables
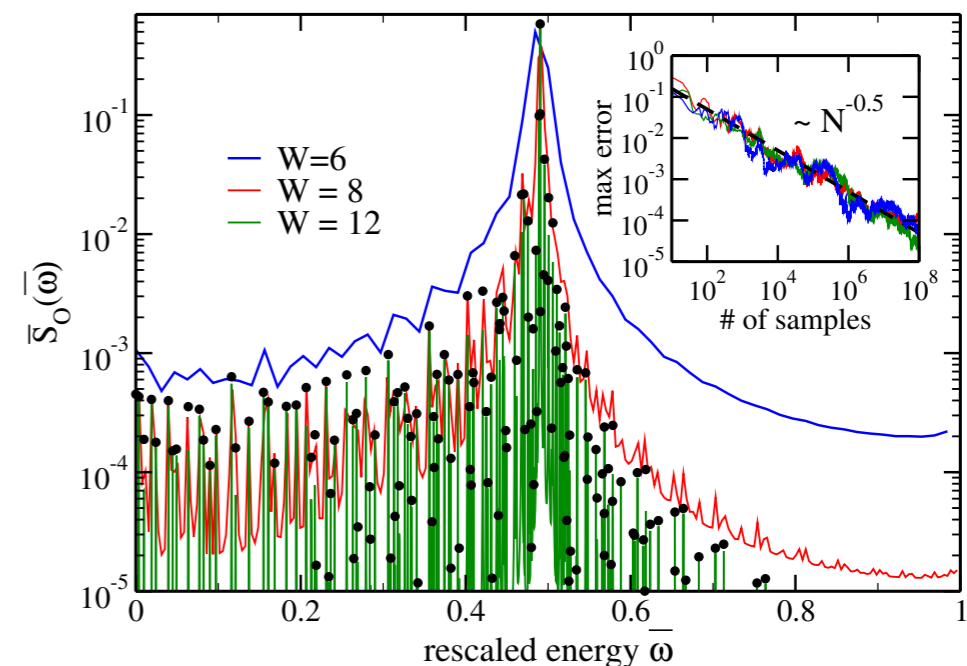
Alessandro Roggero, et al (2018)

Deep Inelastic Scattering and nuclear dependence of the EMC effect

A dependence in x ~ 0.3-0.7 related to probability of NN with r < 1 fm

assumes SU(4) symmetry

Lynn, et al. (2019) arXiv:1903.12587

Summary / Outlook

- More quantitative understanding of neutrinos and neutrino-nucleus interactions is being developed
  - requires combined effort of
  - experiment, HE and NP Theory

- Starting to get a good picture of pairs of nucleons after the vertex, important for identifying final states
- Can be extended to other important regions
  - nuclear effects may be important even in DIS (see EMC effect)

- Important to extract neutrino properties from experiment
  - Mixing angles
  - Hierarchy
  - CP violation
  - Absolute mass scale