Electron and Neutrino Scattering from Correlated Neutrino Pairs

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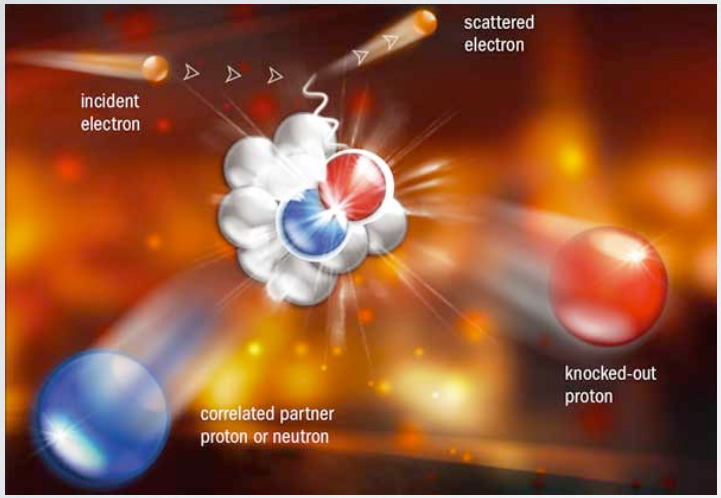
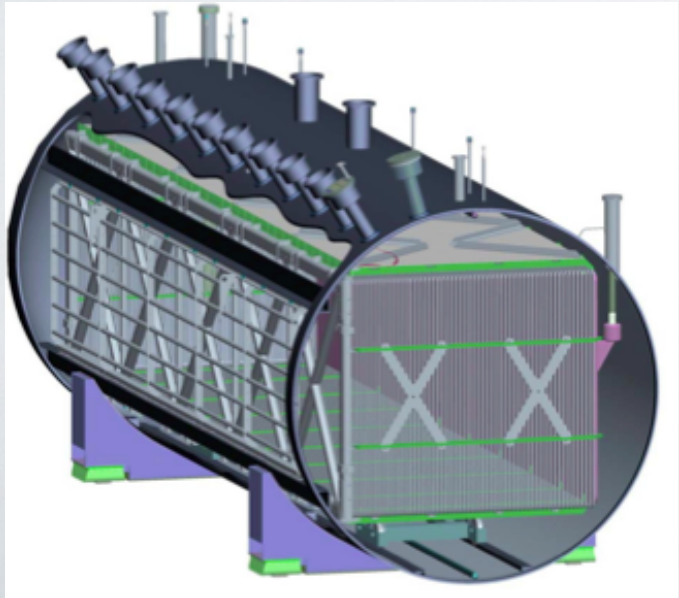


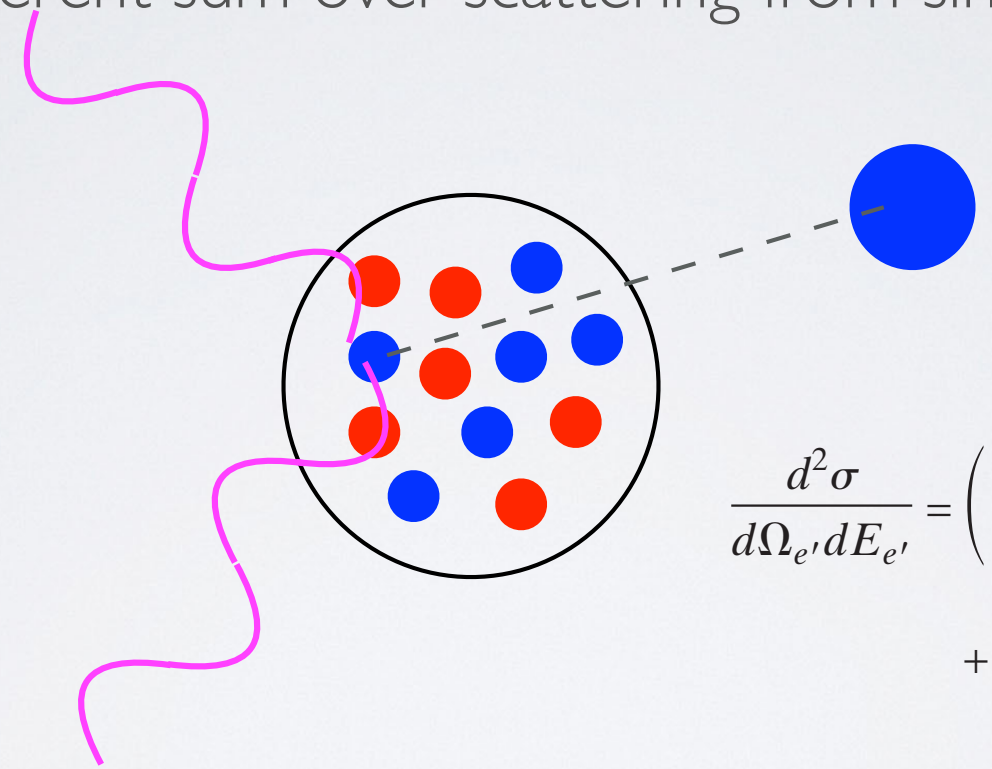


Two-nucleon dynamics (correlations and currents) play important roles across scales of energy and momenta

Quasi-elastic scattering: energies, momenta of the scale of the Fermi momentum and energy or somewhat larger

Scaling with momentum transfer: 'y'-scaling

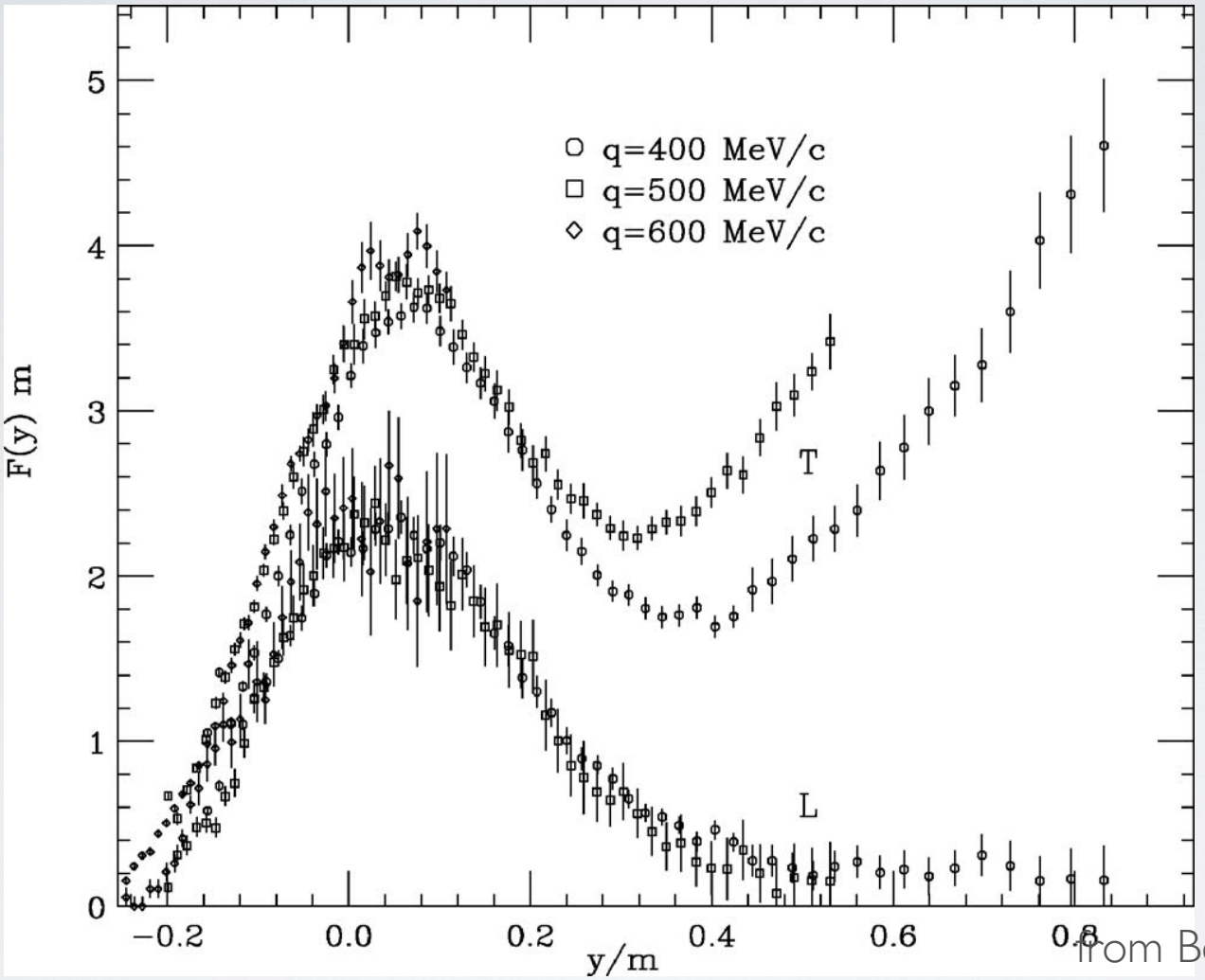
incoherent sum over scattering from single nucleons



$$\frac{d^2\sigma}{d\Omega_{e'}dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4} R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega)\right]$$

In electron scattering we know the energy and momentum transferred to the nucleus very precisely

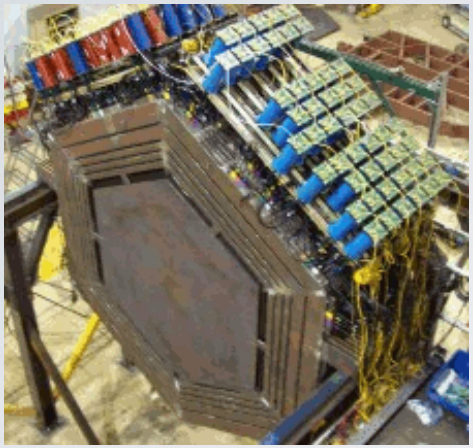
Quasi-Elastic electron scattering: ^{12}C transverse/longitudinal response



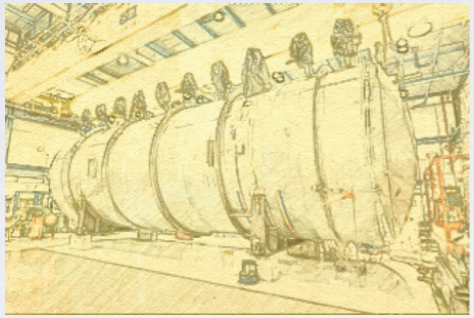
from Benhar, Day, Sick, RMP 2008
data Finn, et al 1984

Scaled longitudinal vs. transverse scattering from ^{12}C
Non-trivial (beyond single-nucleon) physics

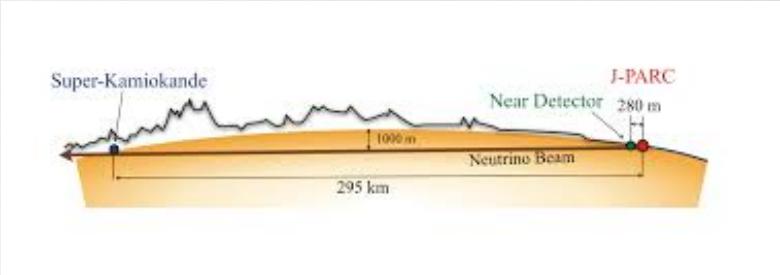
Accelerator Neutrino Experiments



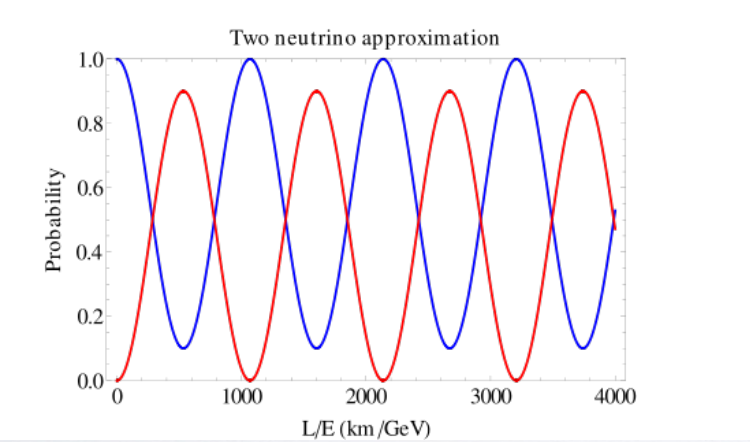
MINERva

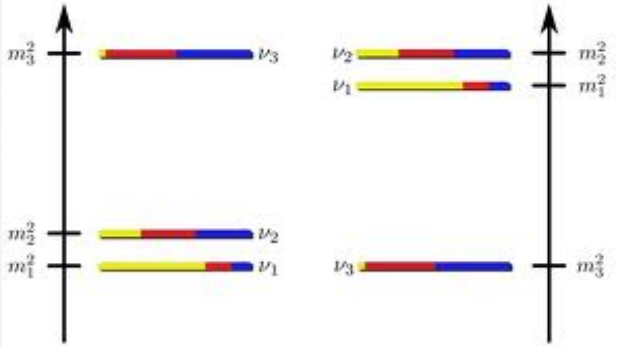


MicroBooNE



SuperK





mass differences,
mixings from oscillations

Neutrinos Oscillations and Masses

Neutrino oscillations first proposed in 1957 by Bruno Pontecorvo, Maki, Nakagawa, and Sakata in 1962

Neutrinos interact with matter in the flavor basis but propagate in the mass basis (in vacuum)

CP-violating phase

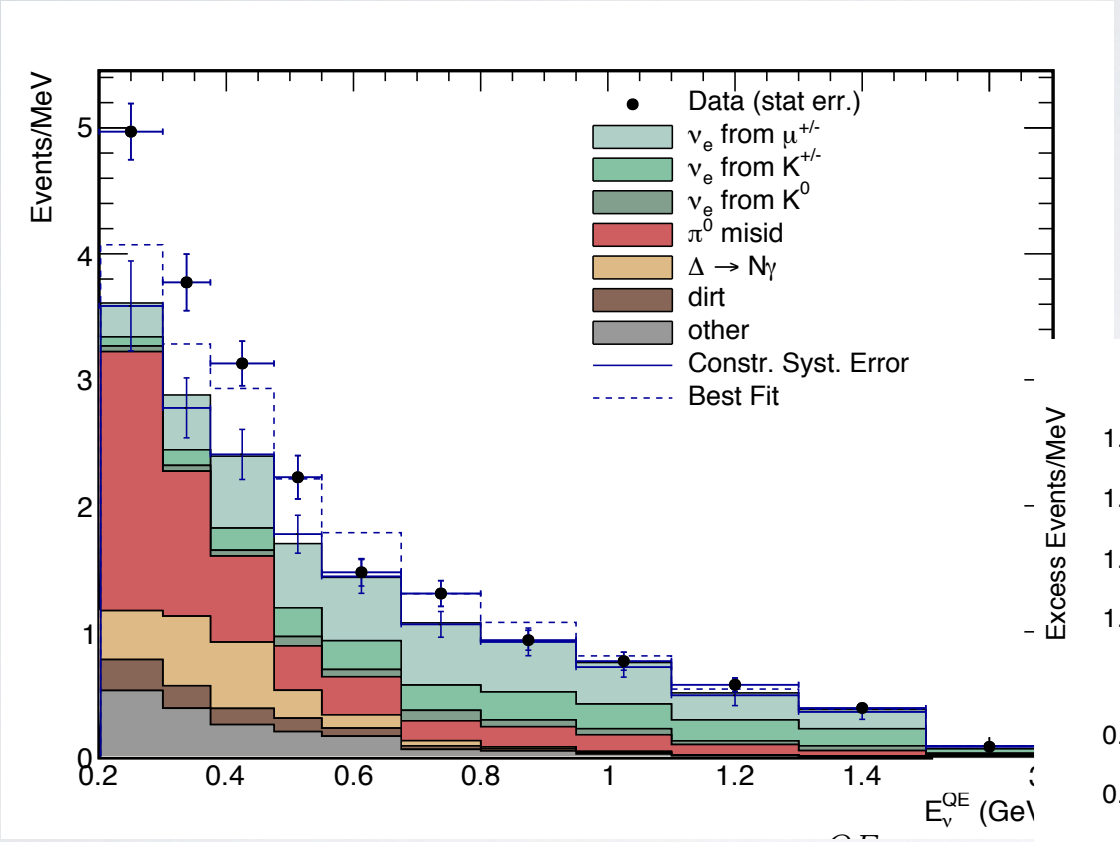
Majorana

$$
\begin{aligned}
U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \\
&= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix} \\
&= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}
\end{aligned}
$$

Mixing angles, CP violating phases, Majorana Phases

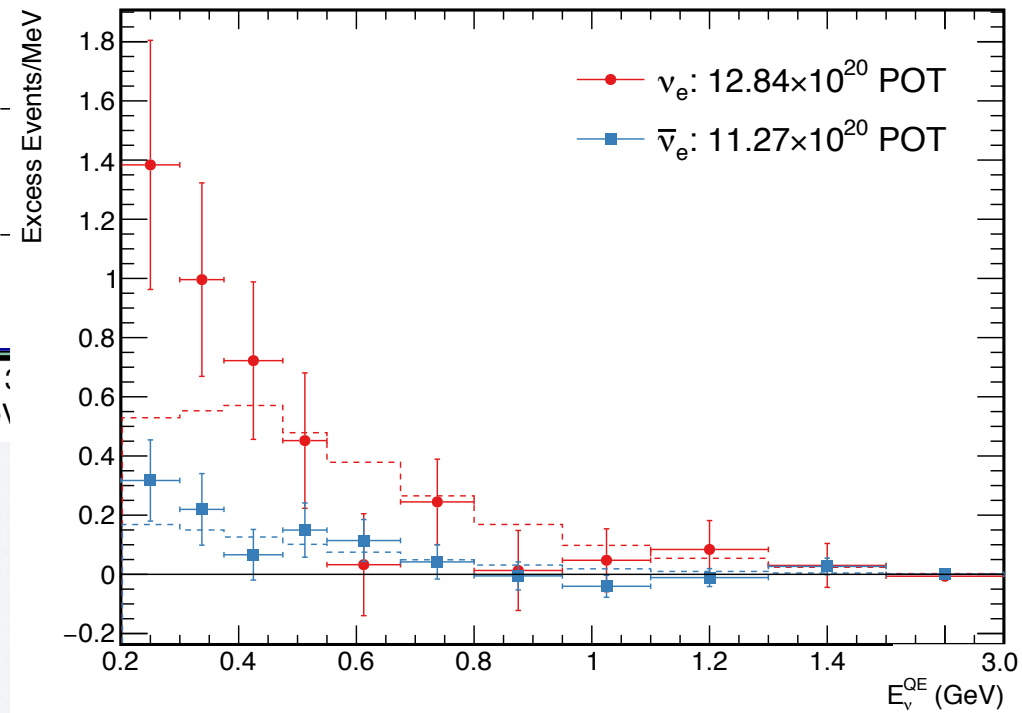
+ MSW effect from forward scattering in matter

MiniBoone - 2018



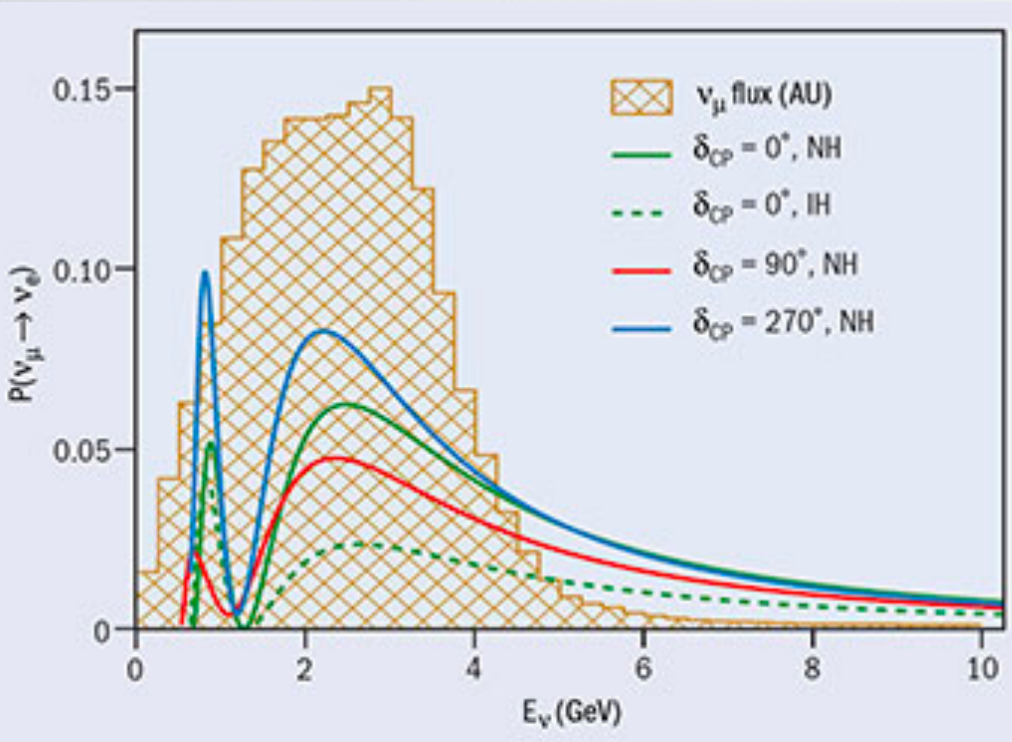
Neutrino mode

Excess in both modes

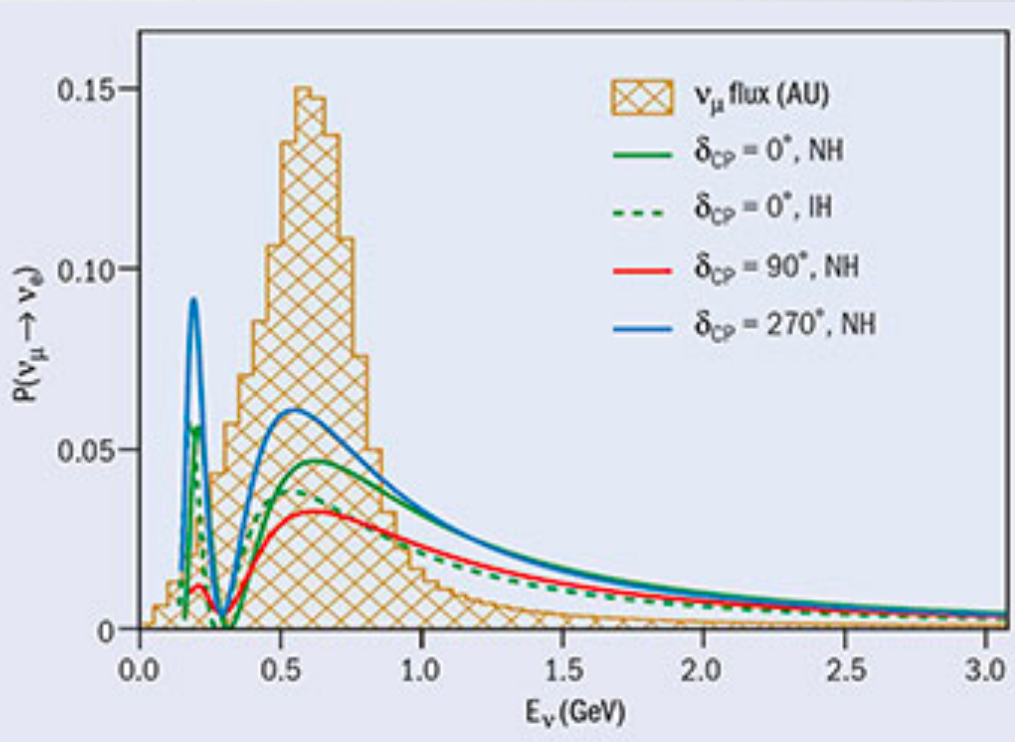


Present/Future Experiments

DUNE

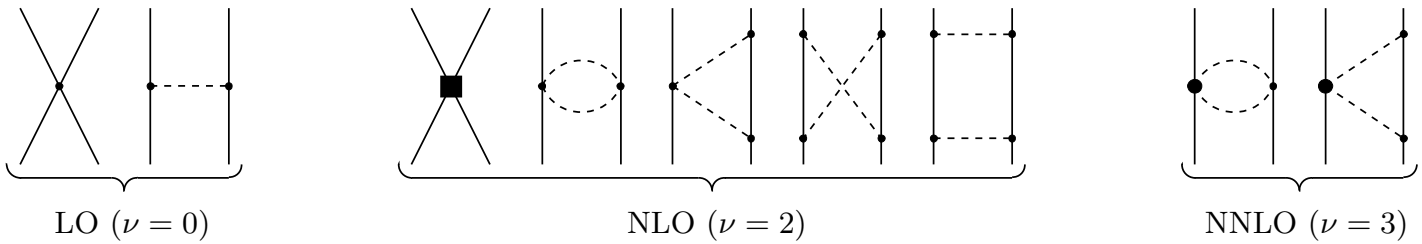


T2K

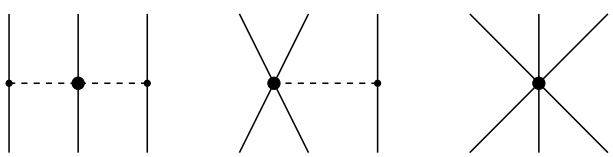


Basic building blocks: Nuclear interactions and currents

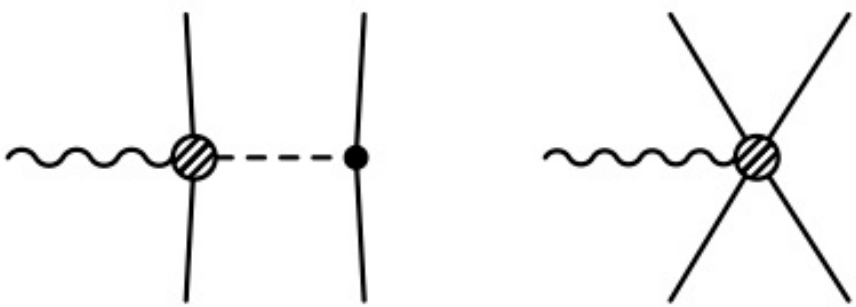
NN interactions



3N interactions

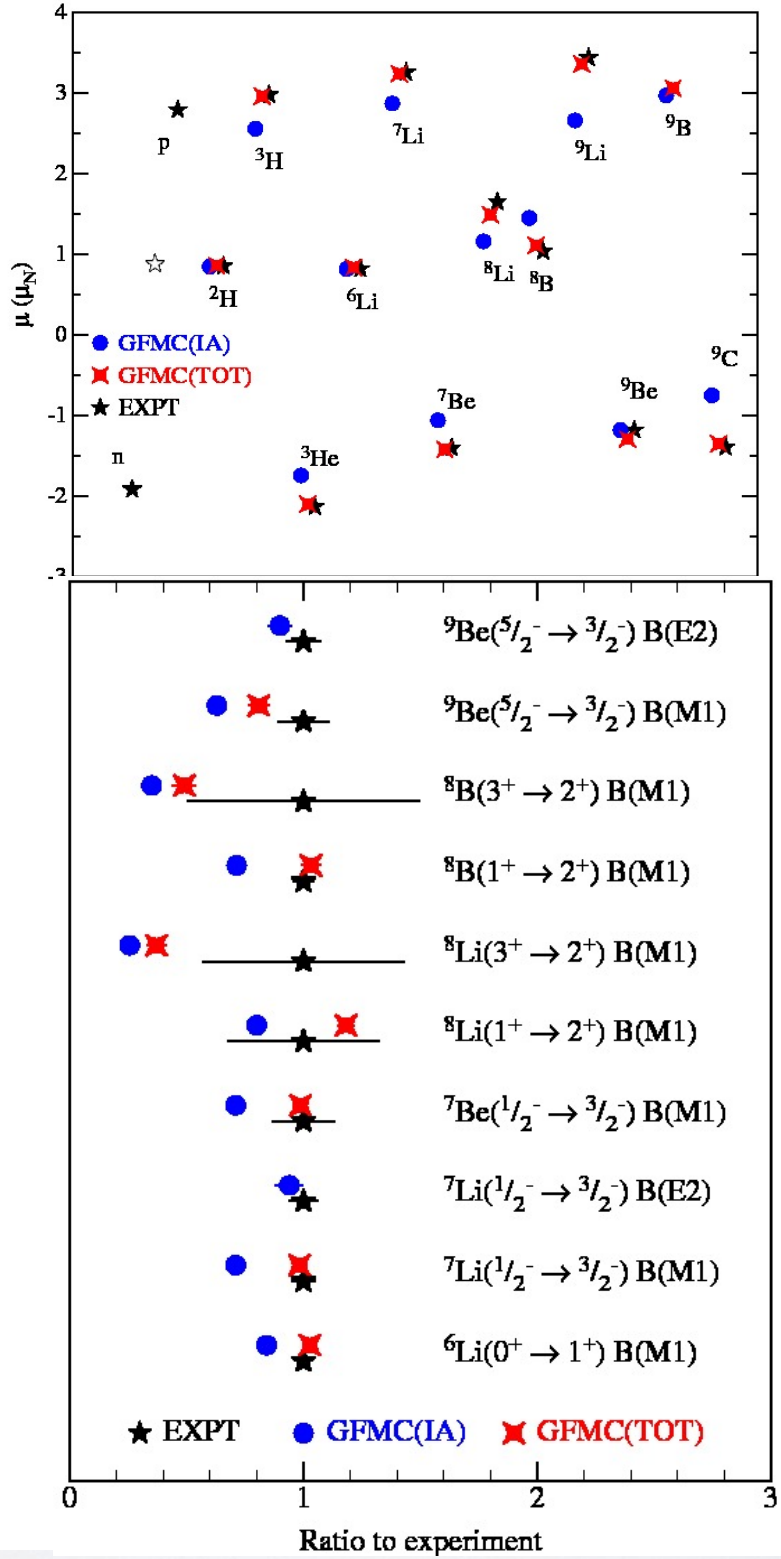


NN currents



Two-nucleon currents are important:

Magnetic Moments and Transitions (q=0, Low energy)



Magnetic Moments

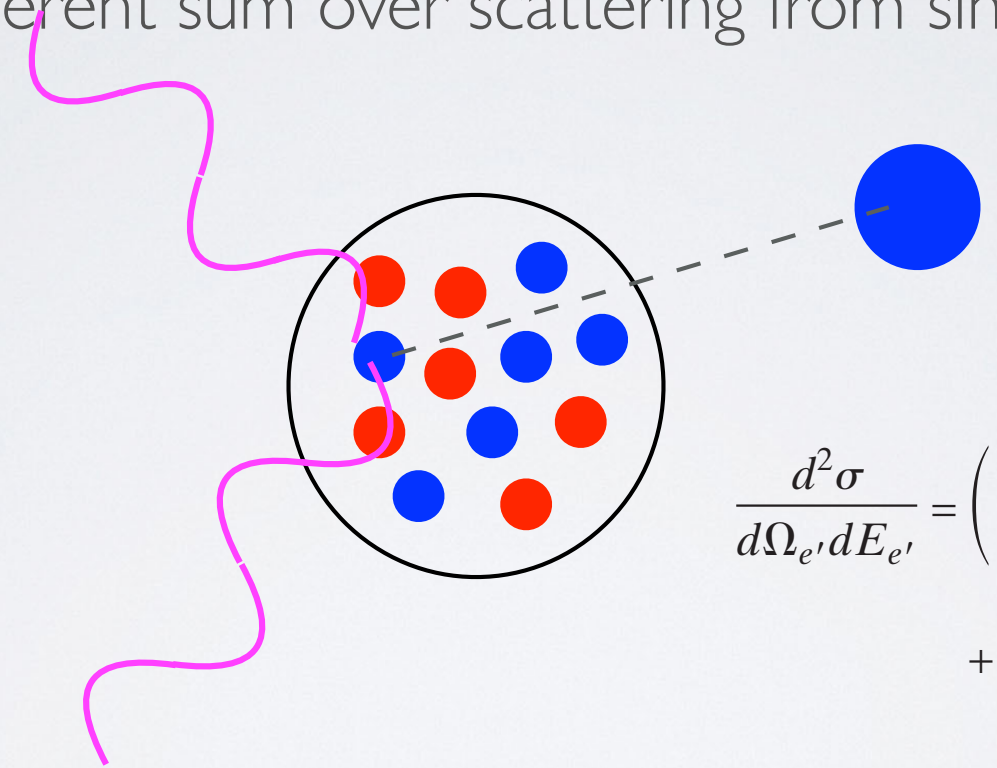
EM Transitions

Wiringa, Pastore, Schiavilla, et al

NUCLEI
Nuclear Computational Low-Energy Initiative

Quasi-elastic scattering: higher p, E

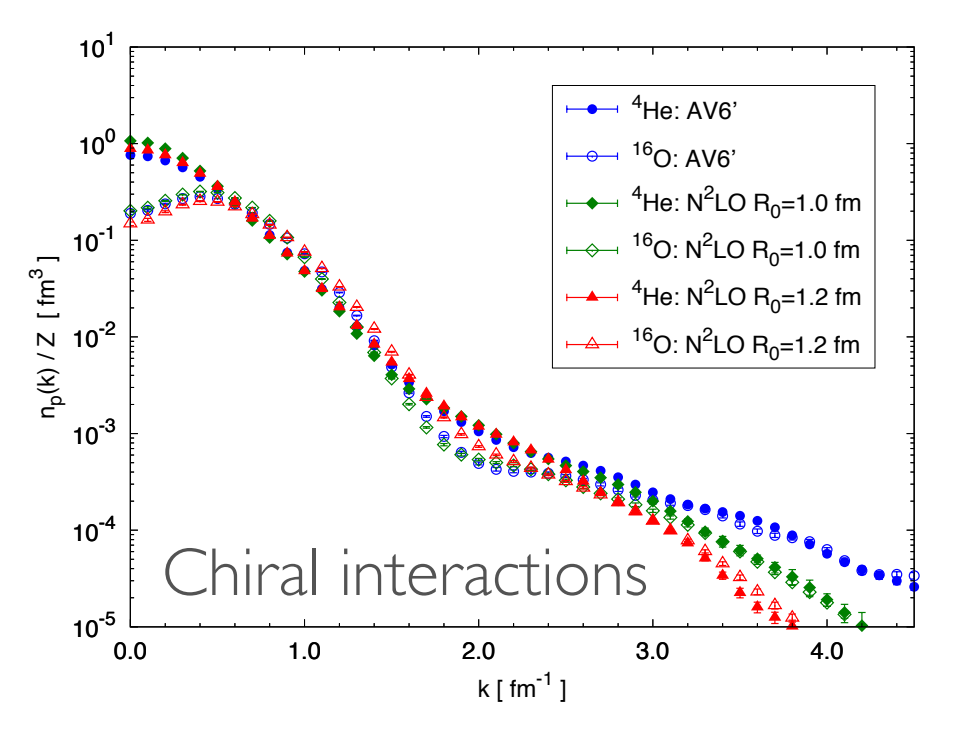
Scaling with momentum transfer: 'y'-scaling
incoherent sum over scattering from single nucleons

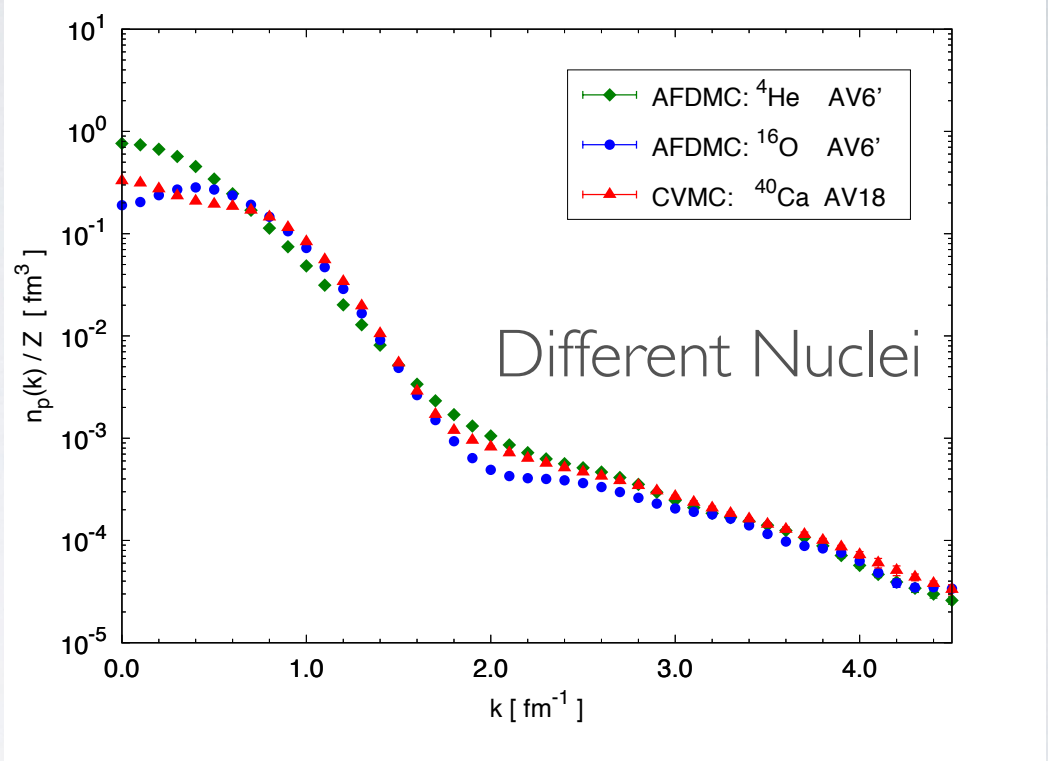


$$\frac{d^2\sigma}{d\Omega_{e'}dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4} R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega)\right]$$

PWIA often good for q >> k_F; used in many fields

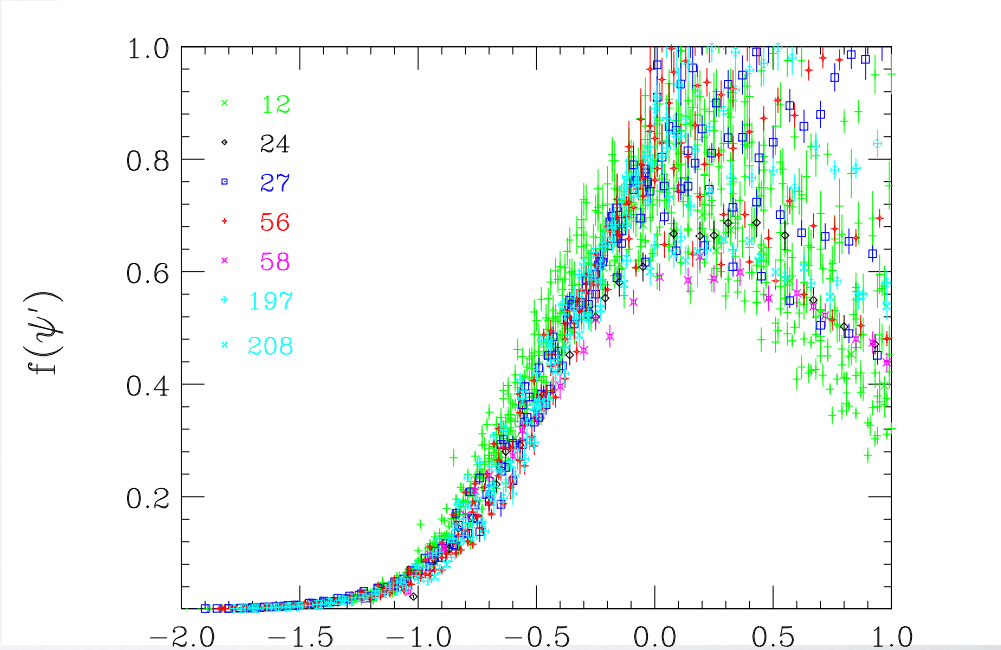
Single-Nucleon Momentum Distributions





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)

Electron Scattering: Longitudinal and Transverse Response

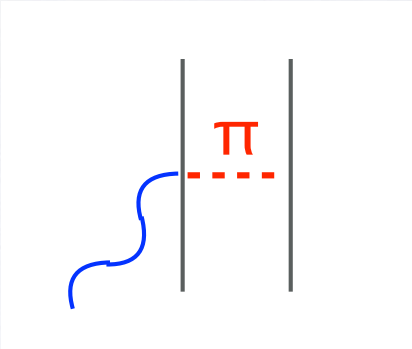
Transverse (current) response:

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

Longitudinal (charge) response:

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

$$\mathbf{j} \;=\sum_i \mathbf{j}_i \;+\; \sum_{i<j} \mathbf{j}_{ij} + \ldots$$



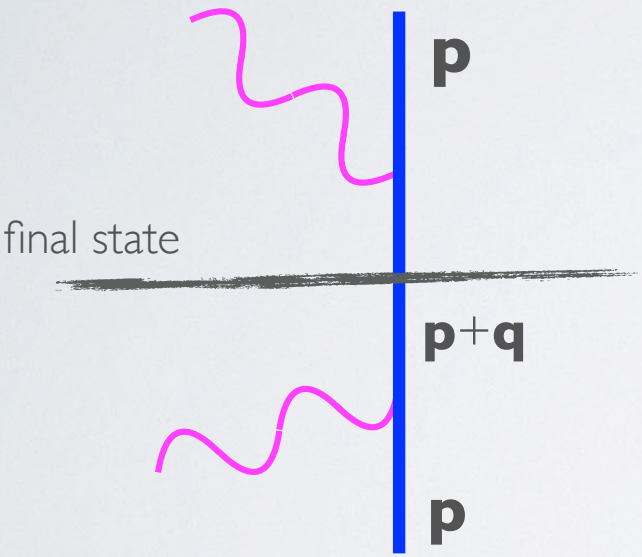
Two-nucleon currents required by current conservation

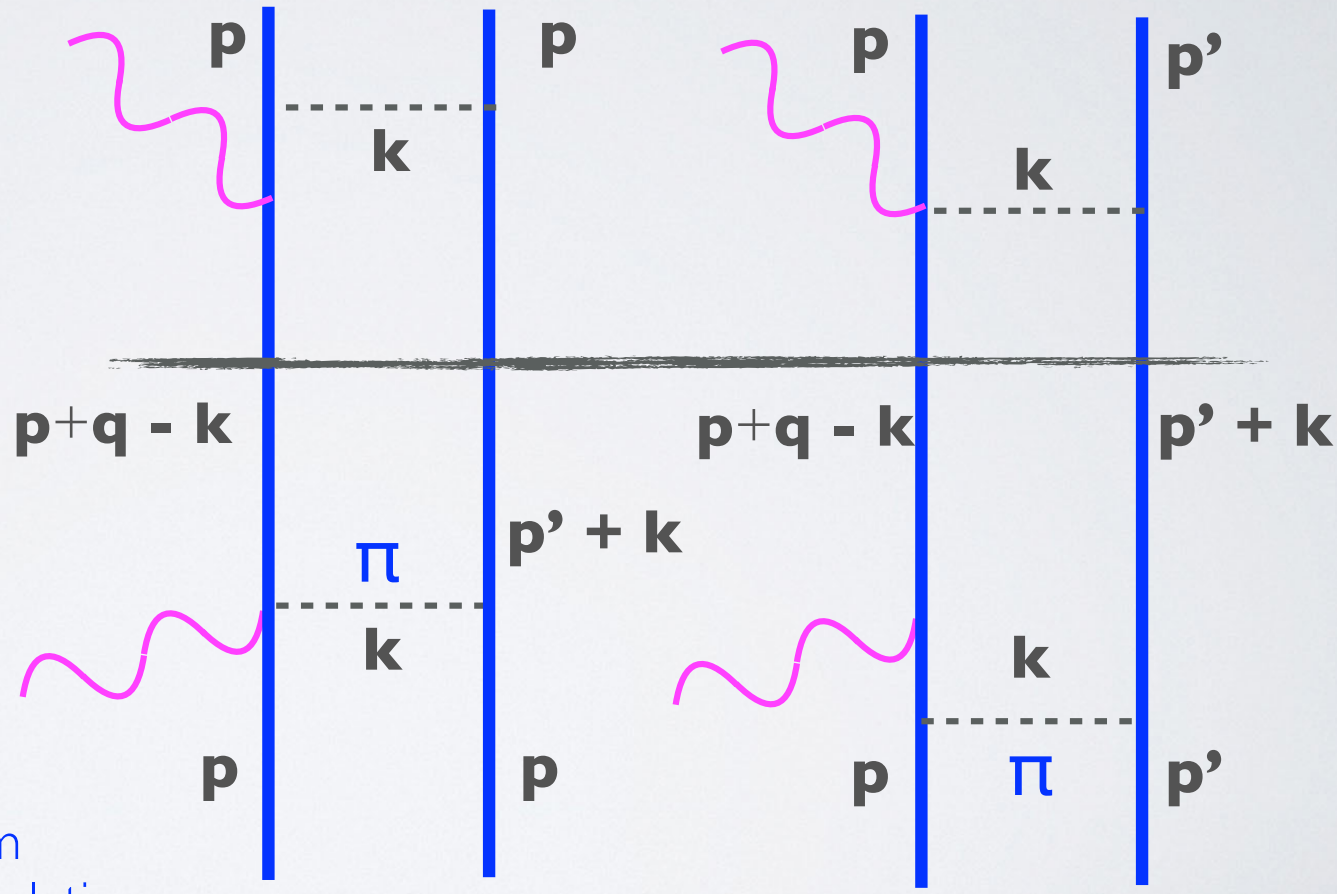
Response depends upon all the excited states of the nucleus

Vector Response: Interference Terms

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

PWIA

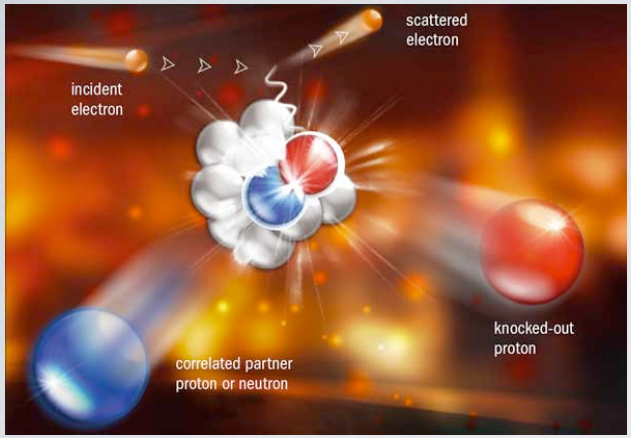




Large enhancement from combination of initial state correlations and two-nucleon currents similar in axial response

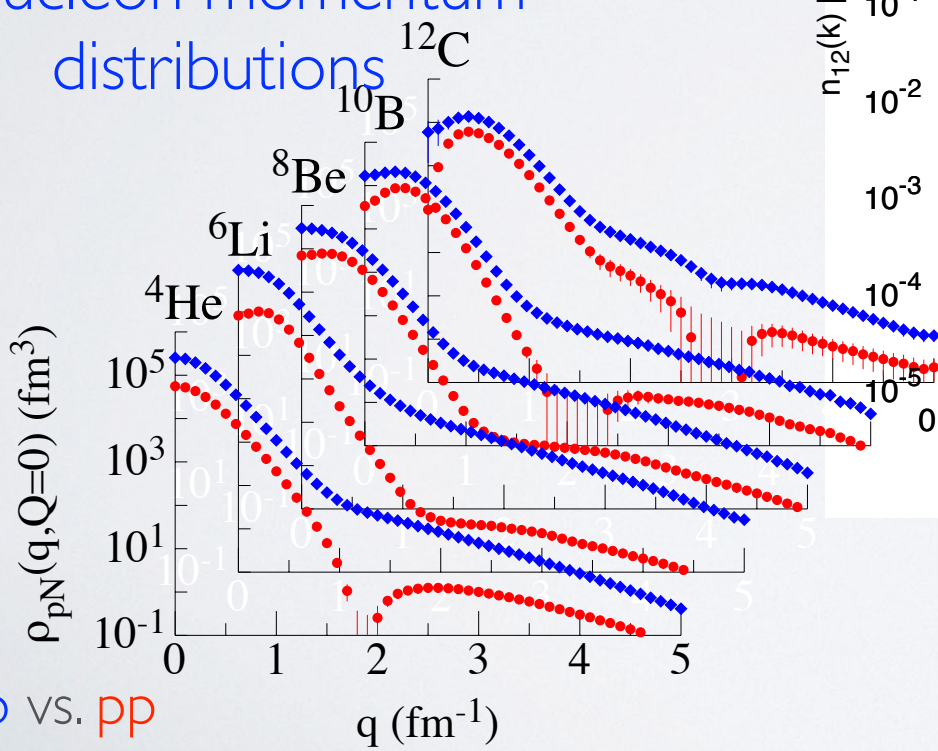
$$\propto \; \sigma_i \cdot \mathbf{k} \; \sigma_i \cdot \mathbf{q} \; (\sigma_j \cdot \mathbf{k})^2 \; (\tau_i \cdot \tau_j)^2 \; v_\pi^2(k)$$

Look at explicit final states:
Back to Back Nucleons (total Q~0)
np pairs dominate over nn and pp



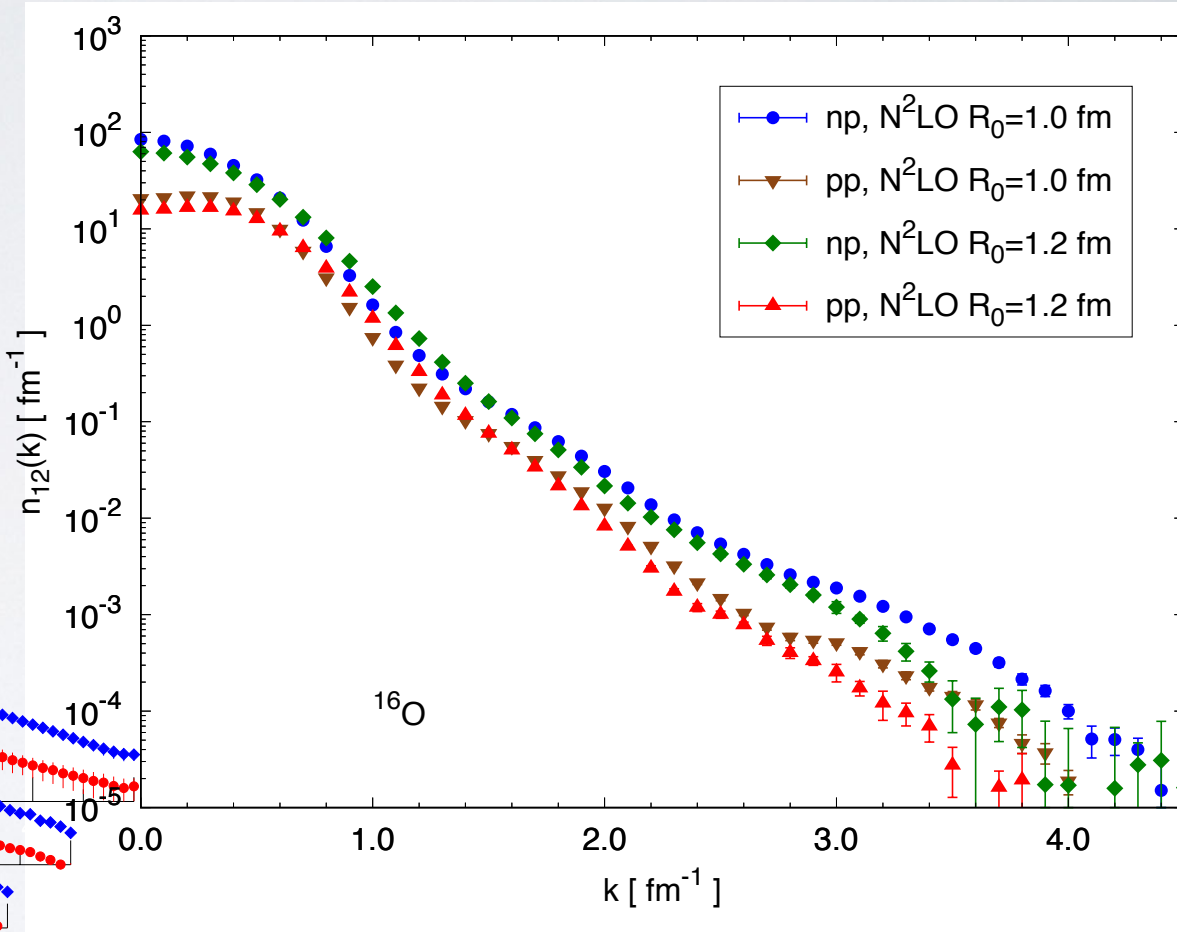
E Piasetzky *et al.* 2006 **Phys. Rev. Lett. 97** 162504.
M Sargsian *et al.* 2005 **Phys. Rev. C 71** 044615.
R Schiavilla *et al.* 2007 **Phys. Rev. Lett. 98** 132501.
R Subedi *et al.* 2008 **Science 320** 1475.

2-nucleon momentum distributions



np vs. pp

Wiringa et al.; Carlson, et al, RMP 2015



Lonardoni, et al, 2018

Euclidean Response

Want to calculate

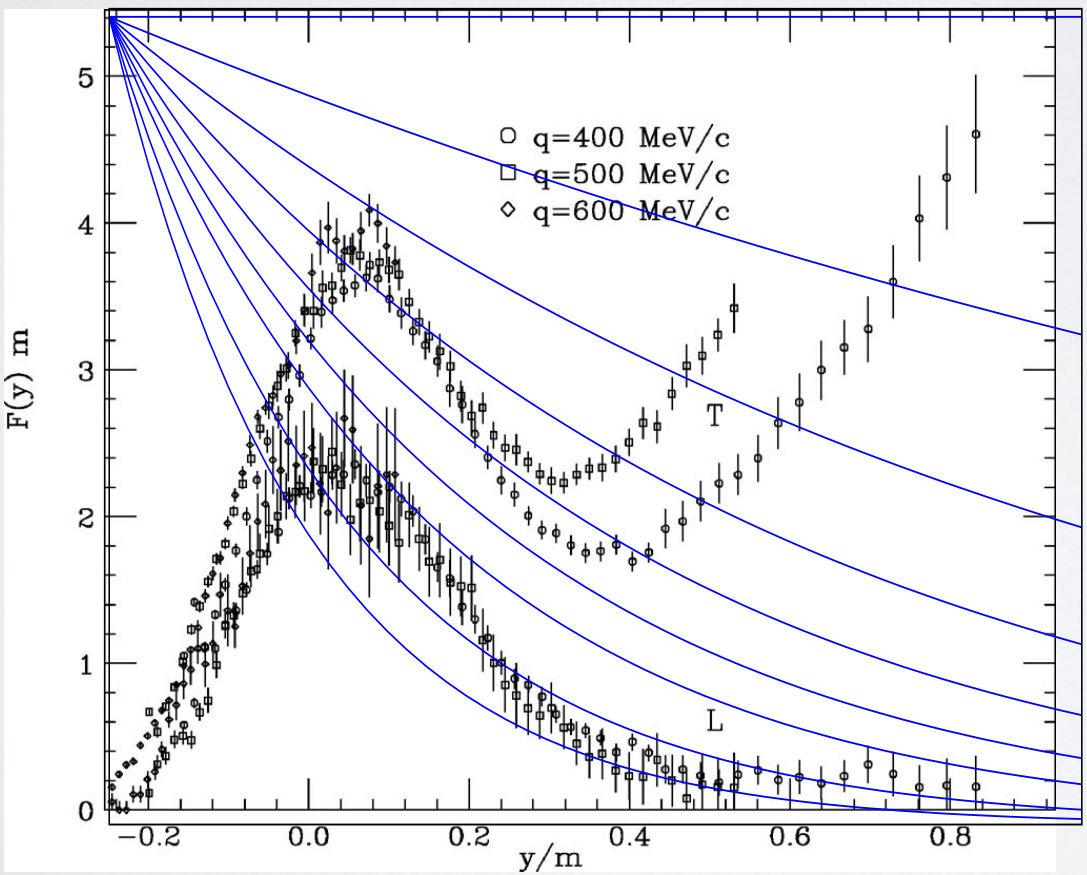
$$R(q,\omega) \;=\; \int dt\; \langle 0|\, \mathbf{j}^\dagger \exp[i(H-\omega)t]\; \mathbf{j}\; |0\rangle$$

Can calculate

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

- `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

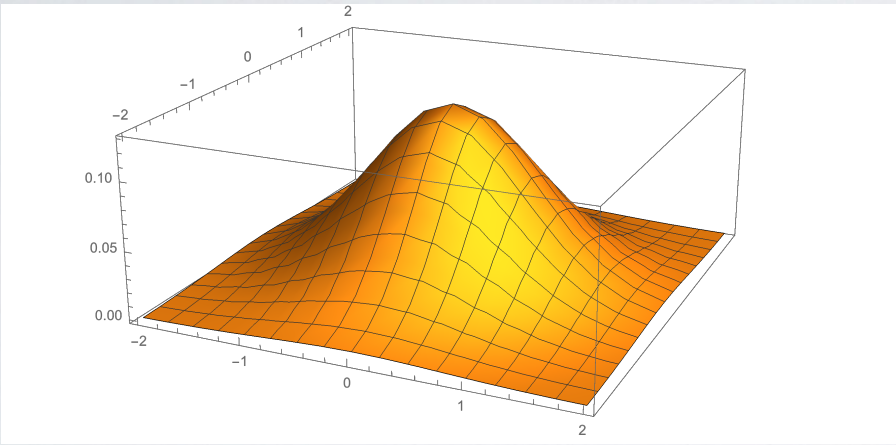


τ

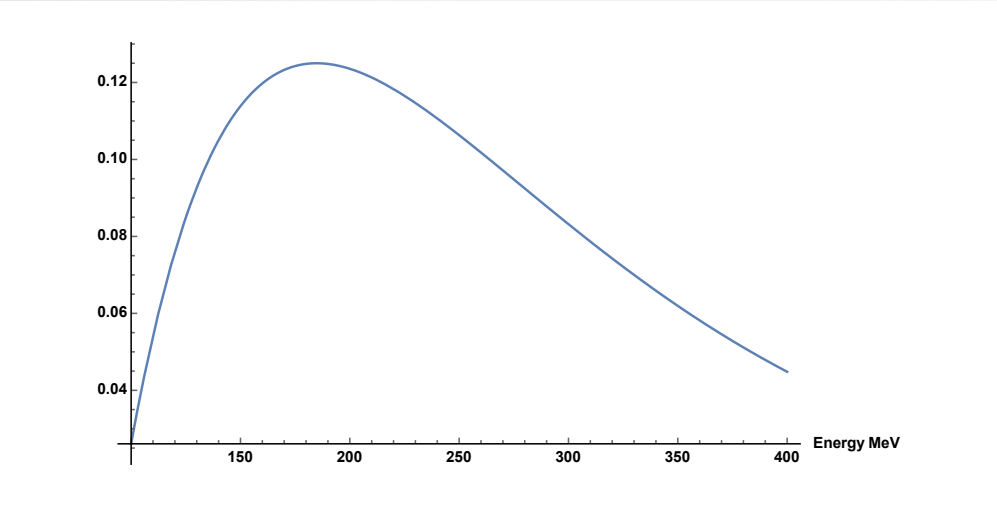
Sum rule → elastic FF^2 w/ increasing τ

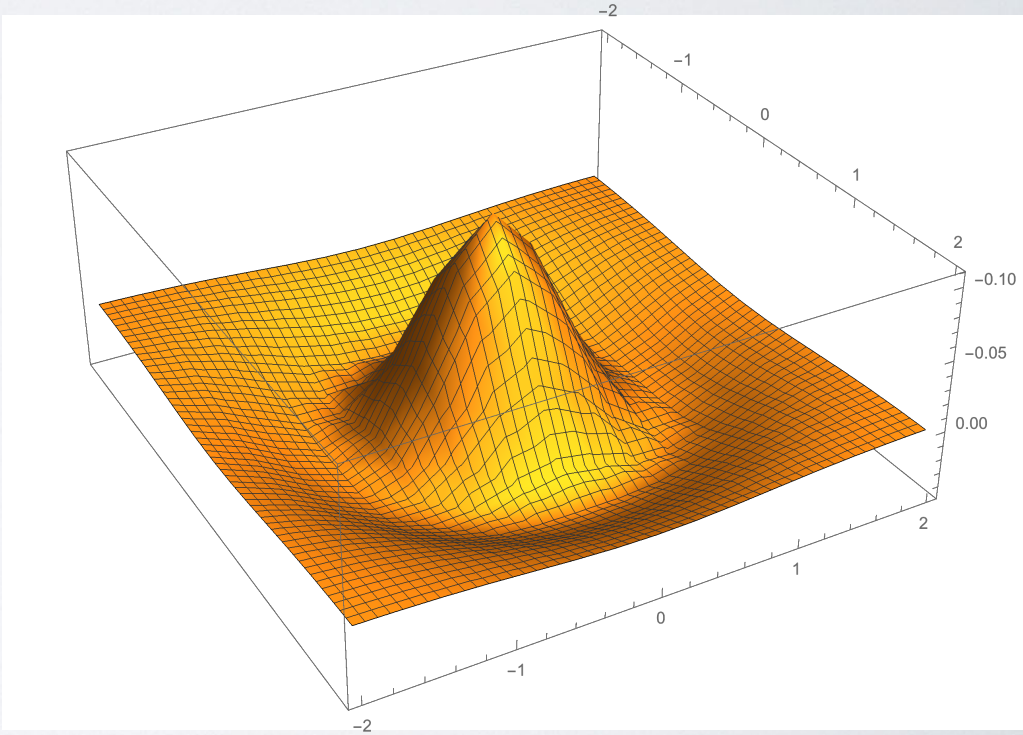
High Energy Inclusive Response is a 'nearly' local operator

Free particle propagator at 1/tau = 66 MeV



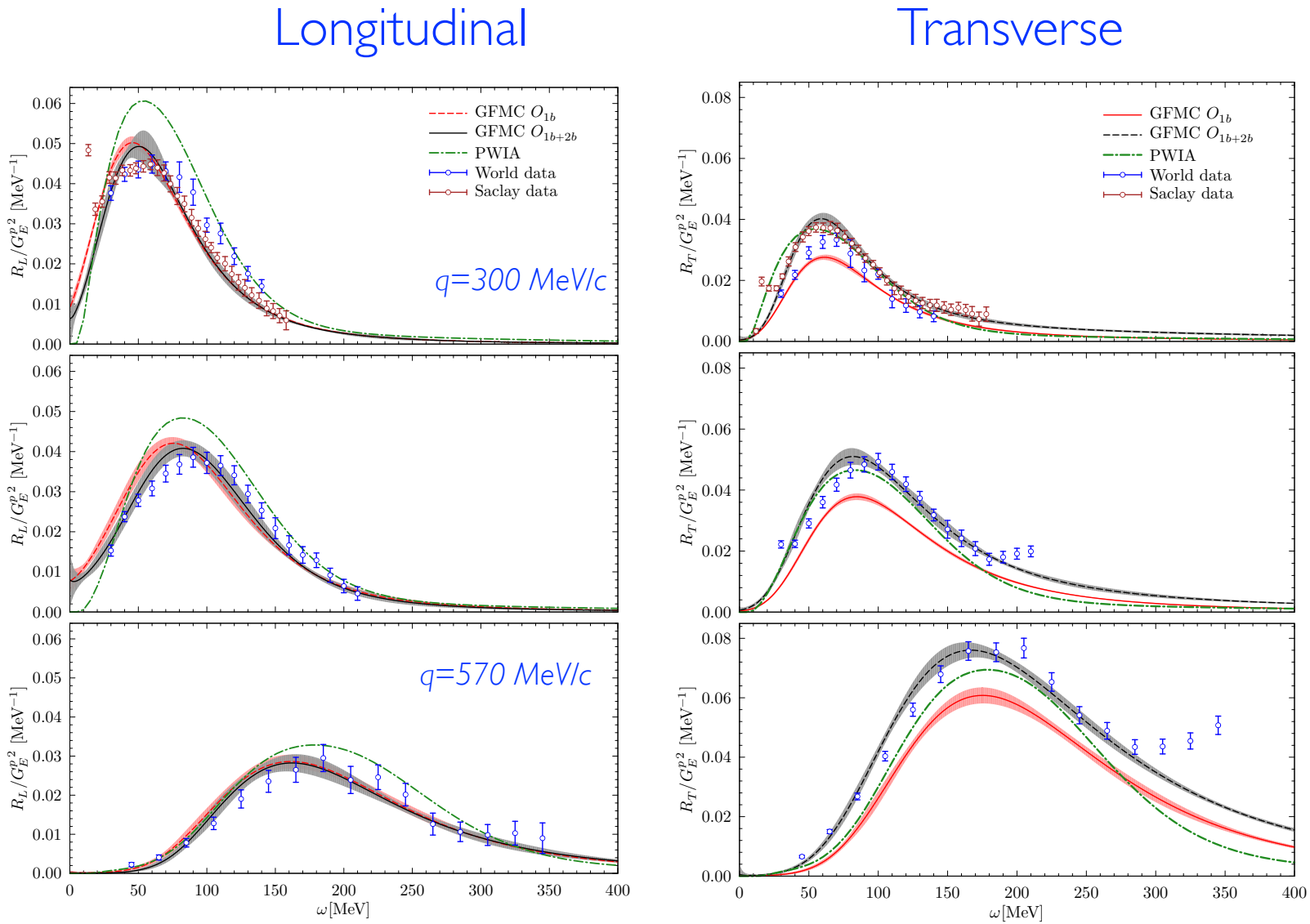
Emphasize energies near 130 MeV





G(1/tau = 132 MeV) - 2 G(1/tau = 66 MeV)

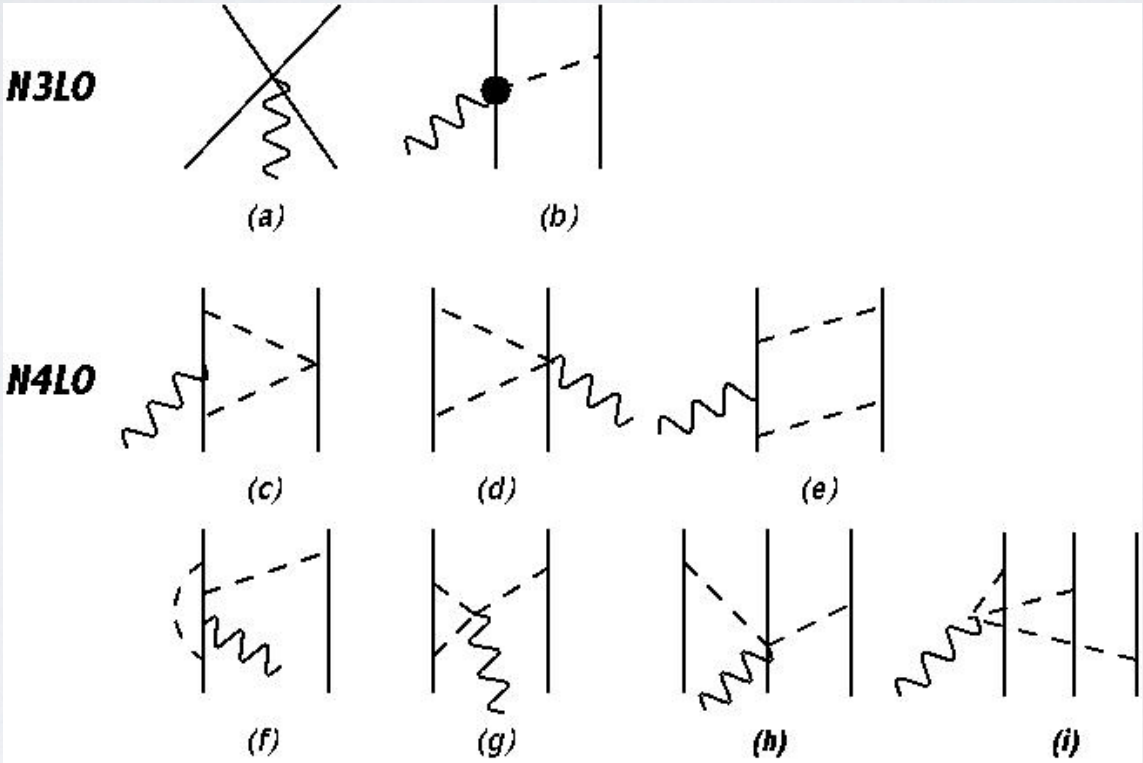
^{12}C EM response



Lovato, et al, PRL, 2016

EM observables well-reproduced

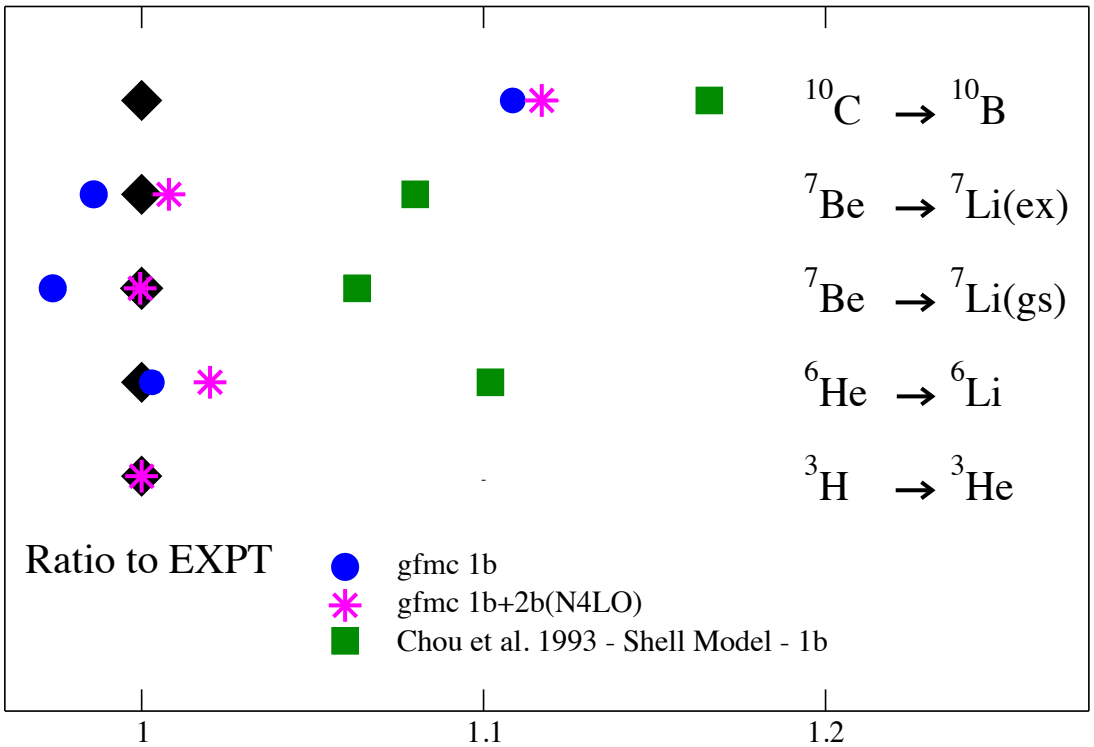
What about neutrinos and weak currents?



Vector and Axial currents: beta decay

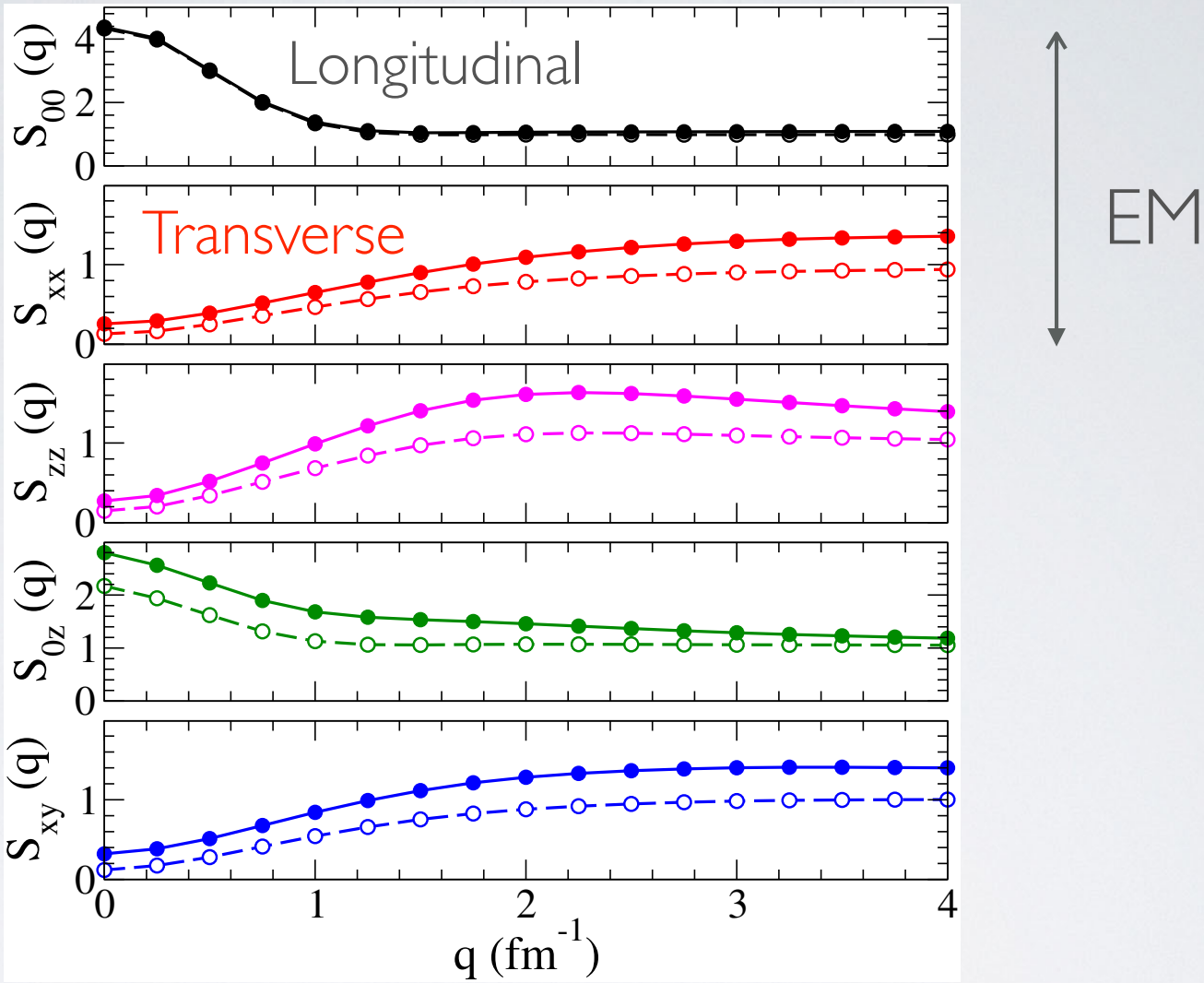
5 response functions in inclusive scattering

Beta Decay in Light Nuclei



- 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

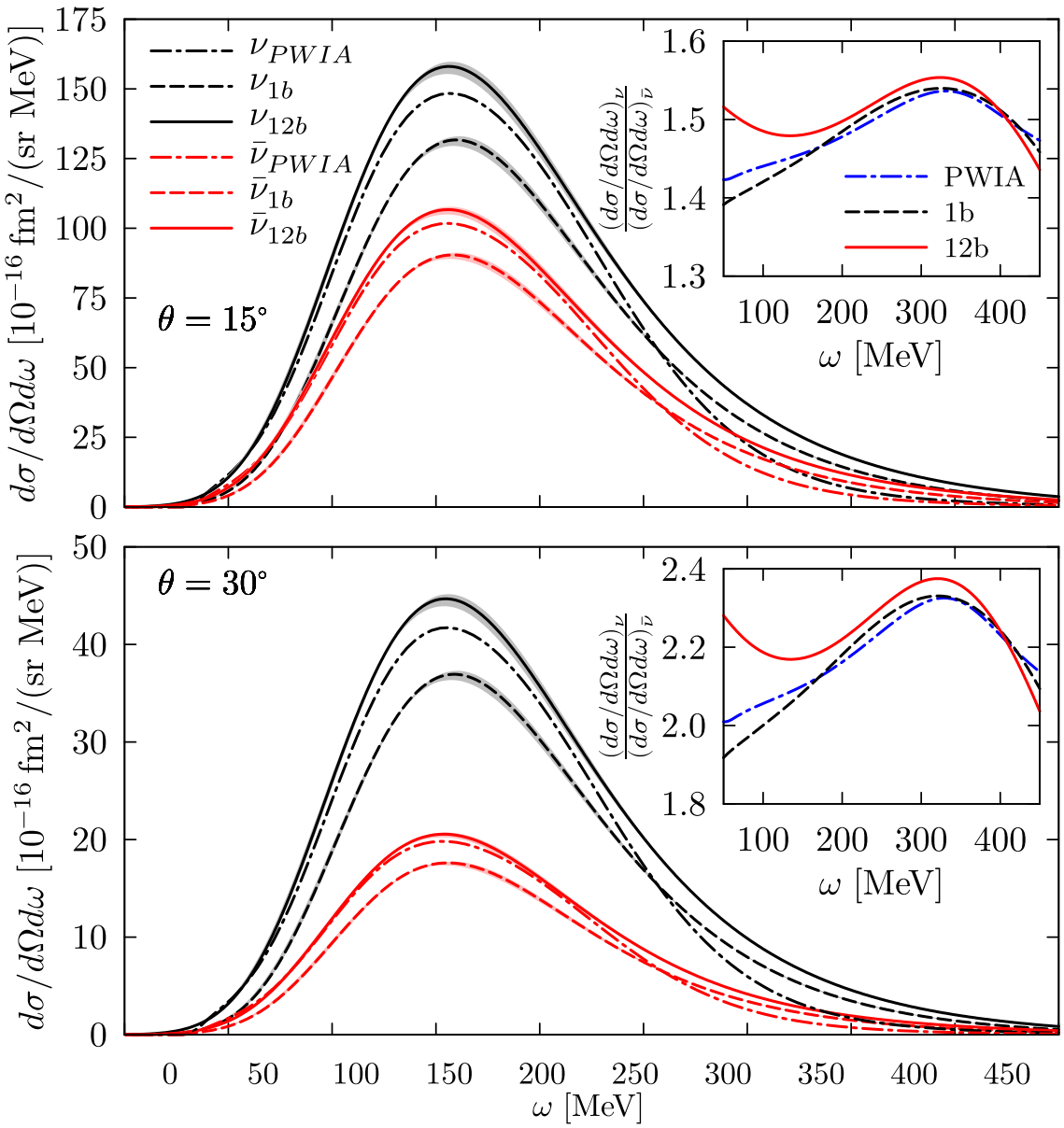
Sum rules in ^{12}C: neutral current scattering



Lovato, et. al PRL 2014

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

Neutral Current Cross Sections ^{12}C



ν

anti-ν

Lovato, et al, 2018

Neutral Current Response/Cross Sections ^{12}C

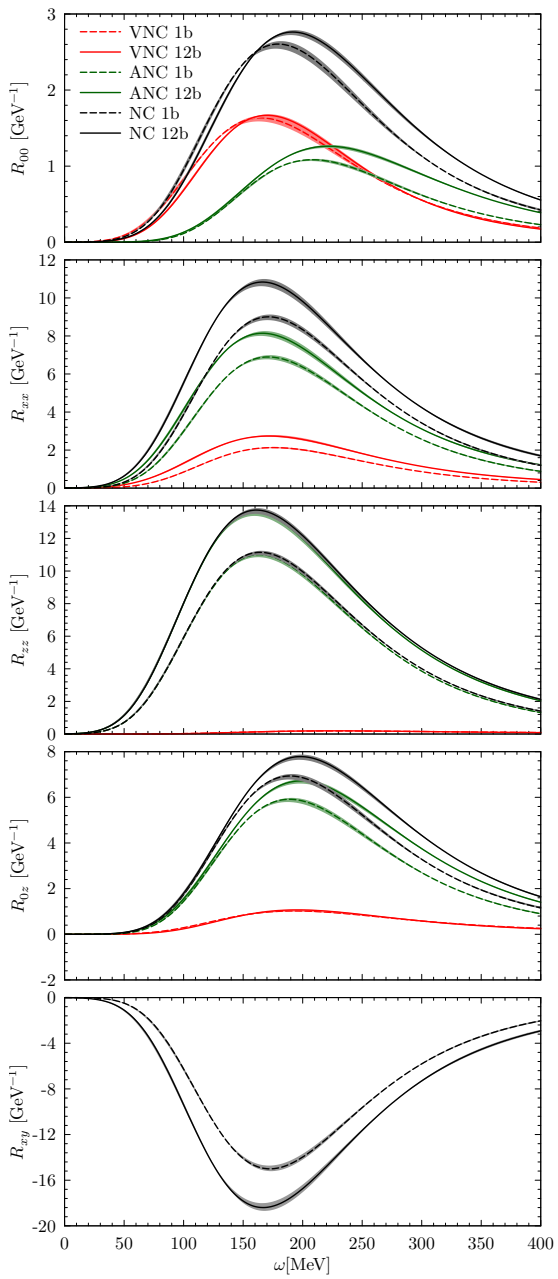
Response functions

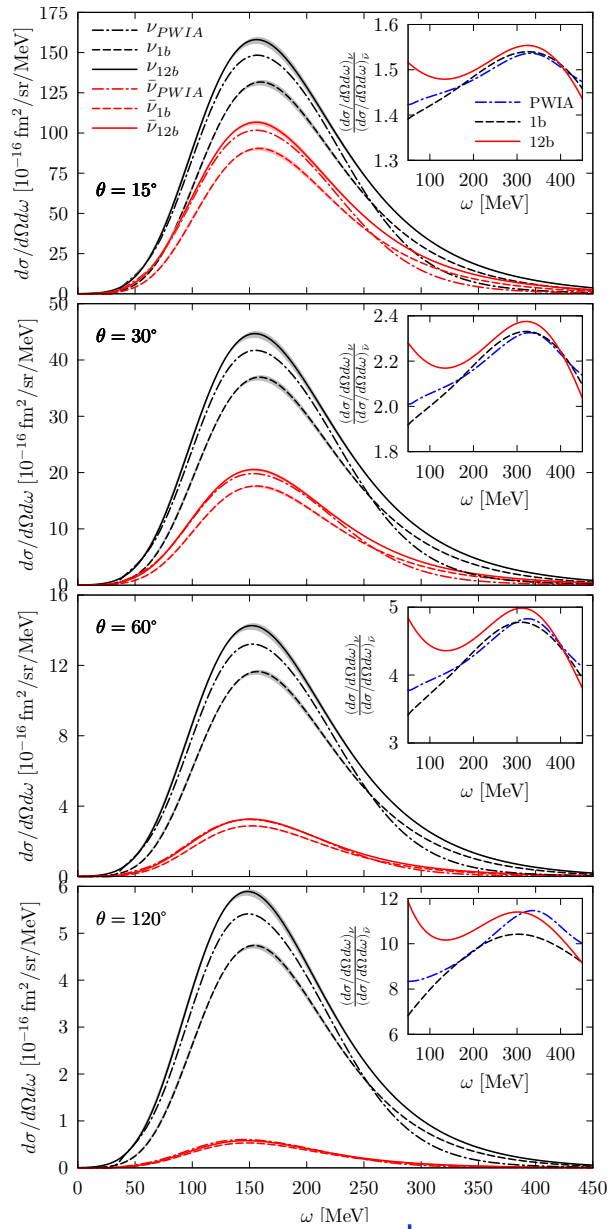
Cross sections

Vector

Axial

Total





anti-ν

ν

Lovato, et al, 2017

Short-Time approximation (Pastore, et al)

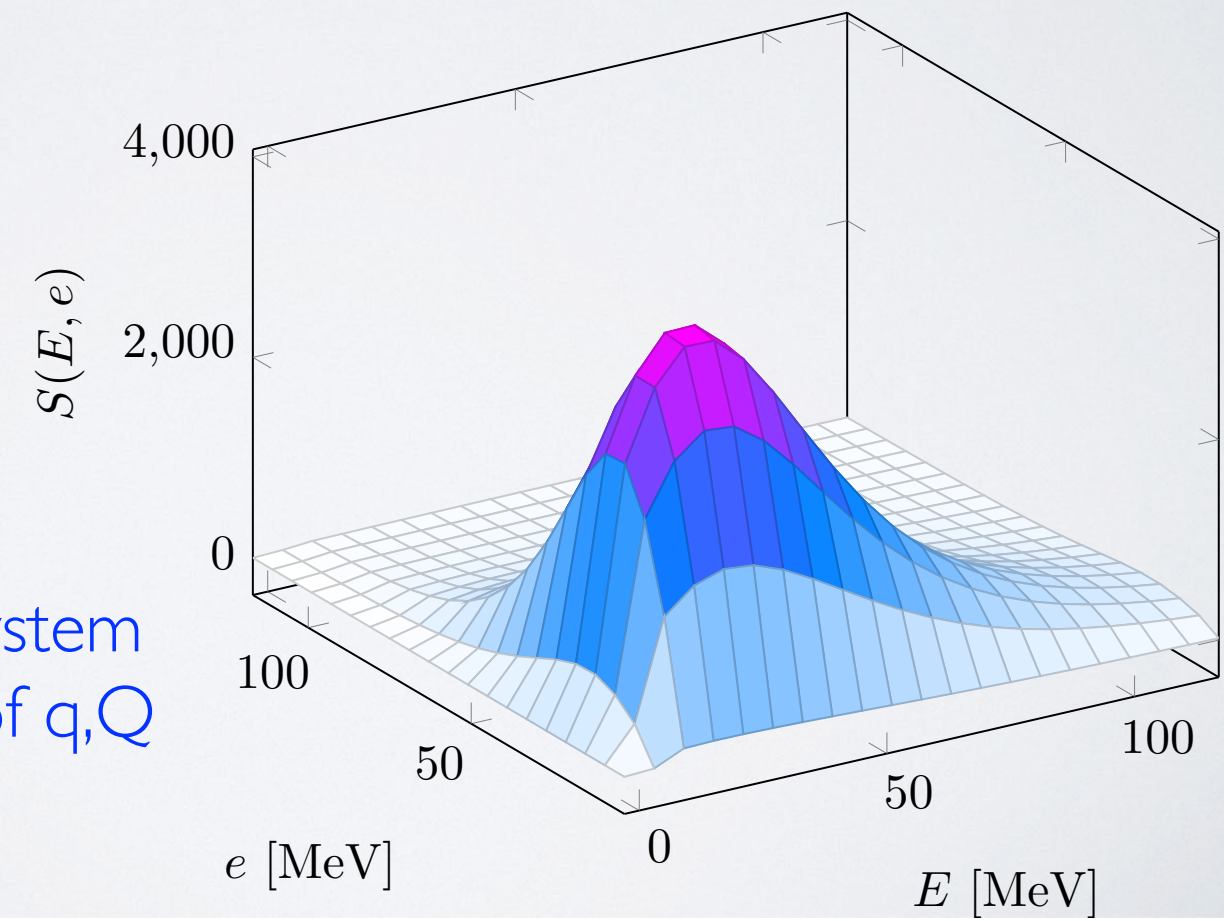
$$R^O(q,\omega) = \frac{\int d\Omega_q}{4\pi} \sum_f \langle \Psi_0 | \mathcal{O}^\dagger(\mathbf{q}) | \Psi_f \rangle \langle \Psi_f | \mathcal{O}(\mathbf{q}) | \Psi_0 \rangle \delta(E_f - E_0 - \omega),$$

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

Factorize at the two-nucleon level:

$$\langle \mathbf{R}', \sigma', \tau' | exp[-iH_{ij}t] | \langle \mathbf{R}, \sigma, \tau \rangle = \sum_f \langle \mathbf{R}', \sigma', \tau' | \Psi_f \rangle \exp[-i\omega_f t] \langle \Psi_f | \mathbf{R}, \sigma, \tau \rangle,$$

Transverse Density $q = 300$ MeV



Insert spectral representation of 2N system response as a function of q,Q at the vertex

Short-Time approximation (cont'd)

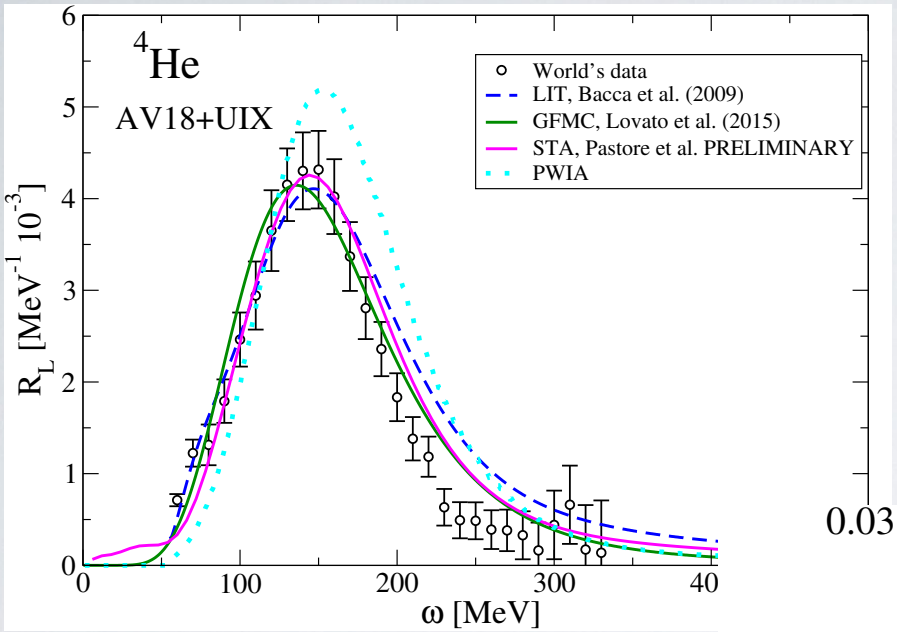
- PWIA or spectral function at 1-body level

- Correct sum rules of the response
  Full ground state correlations and Pauli Principle
  'Nearly' correct energy-weighted SR

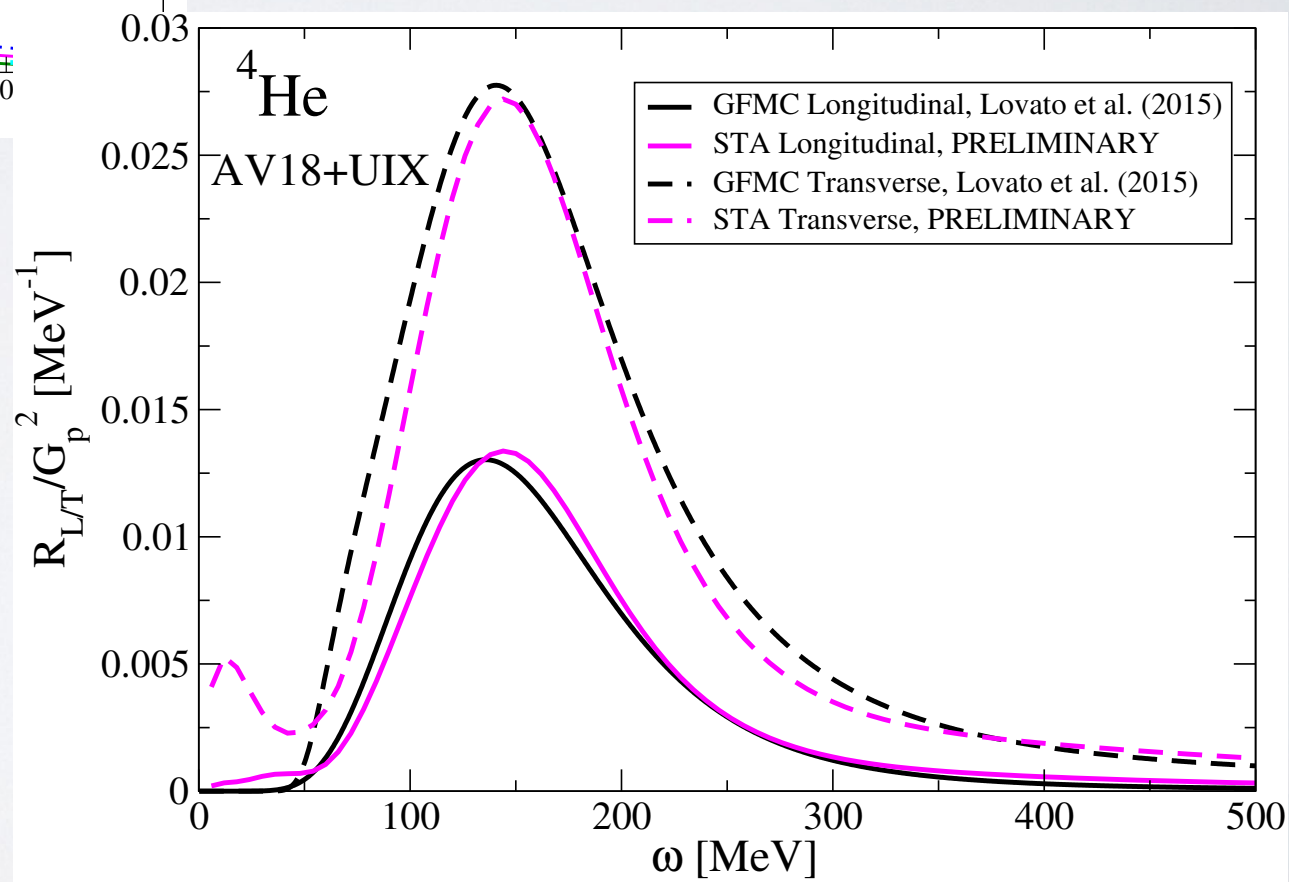
- Some information on exclusive channels
  must combine with (classical) event generators

- No knowledge of low-energy thresholds, etc…
  but can combine with information from
  other calculations e.g. threshholds, $S(q,\tau)$, …

How well does it work?



q = 500 MeV/c



Applications:

- Quasi-elastic neutrino and electron scattering
  (can it be extended to higher energies?)
- Neutrinos in astrophysical environments
  (neutron star cooling, finite T, …)
- Some exclusive information:
  Back-to-back nucleons (do 2N currents play a role ?)
  np vs pp pairs, etc.
- Other weak interactions (muon capture,
  single and double beta decay, …)
- Unitarity Fermions (spin and density response)

Questions:

- Can this be matched to high-energy theories
  of 2 or 3 nucleons, pions, deltas, QCD,… ?
- How to improve the method, other applications, …