Neutrinos & Nuclei

56th International meeting on Nuclear Physics

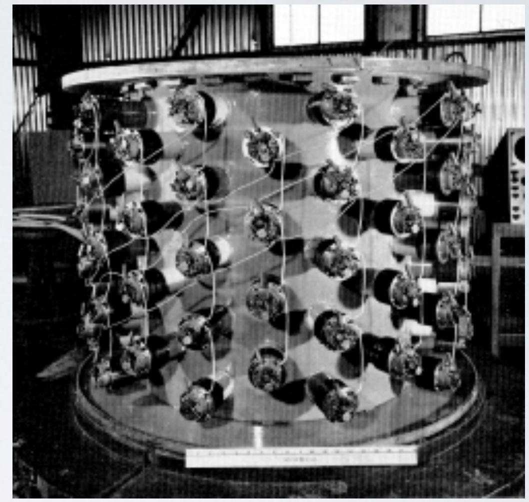
Beta Decay
Accelerator Neutrinos (Quasi-elastic)
Double Beta Decay

collaboration with:
S. Pastore
A. Lovato
D. Lonardoni
S. C. Pieper
R. Schiavilla
R. B. Wiringa

Neutrinos

Neutrinos proposed by Pauli in 1930 to conserve energy, momentum, and angular momentum in nuclear beta decay.

$$n \rightarrow p + e^- + \bar{\nu}_e$$



In 1956 Reines and Cowan detected anti-neutrinos from Savannah River reactors:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

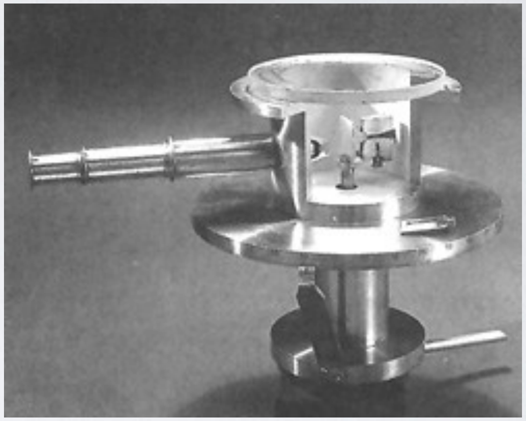
through coincidence of e+e- gamma rays and neutron capture.
Reines was a LANL T-division employee at the time.

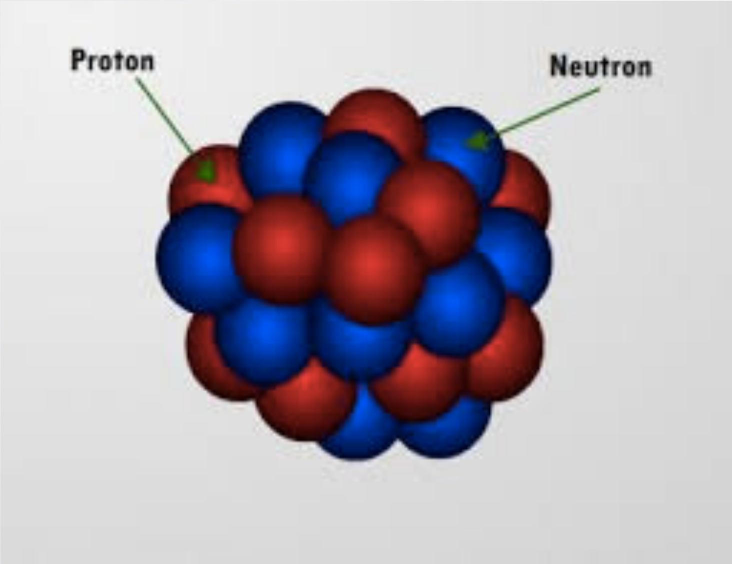
Reines and Cowan were awarded the Nobel Prize in 1995.

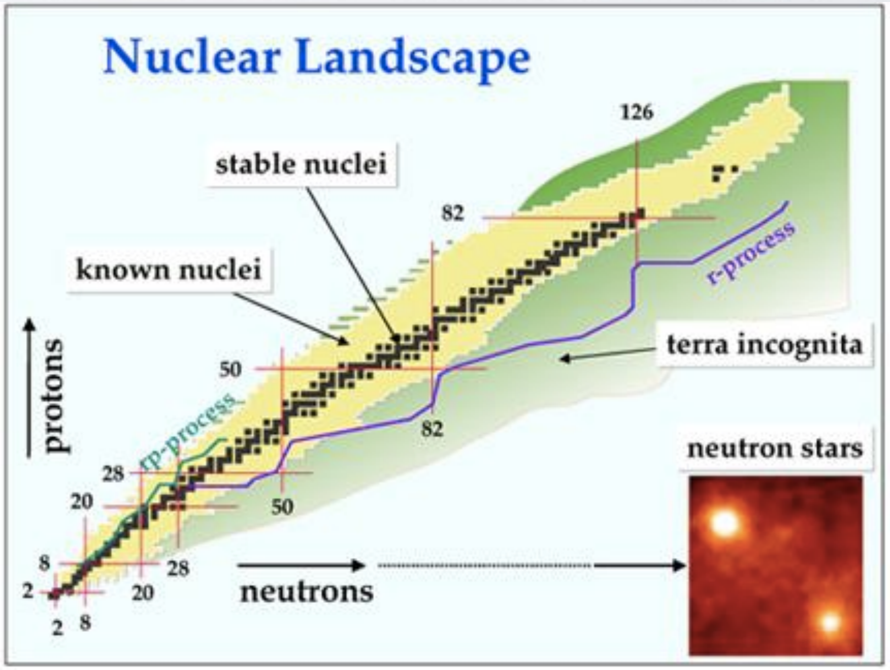
Reines and Cowan discovered the electron (anti-) neutrino.
Later Lederman, Schwartz and Steinberger detected muon neutrino, receiving the Nobel Prize in 1988.

Nuclei

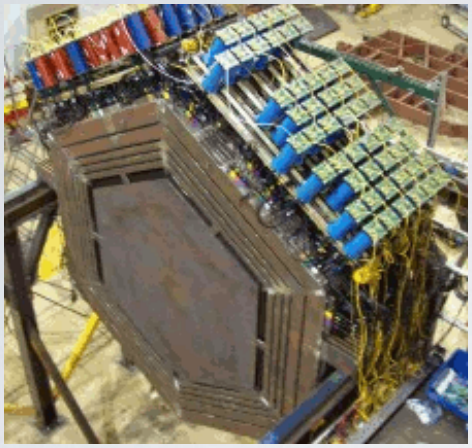
Rutherford
Geiger-Marsden apparatus (~1910)



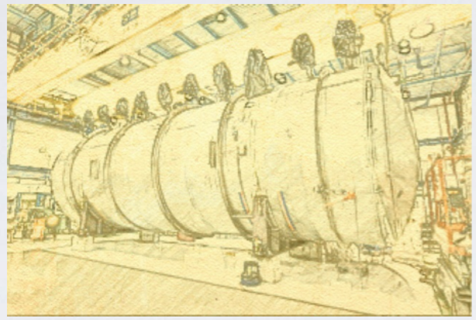




Why study neutrino-nucleus scattering (accelerators) ?

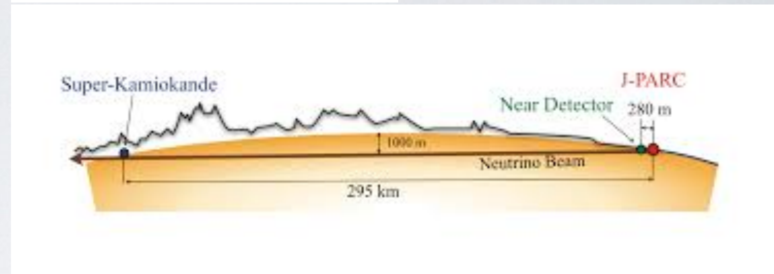


MINERva

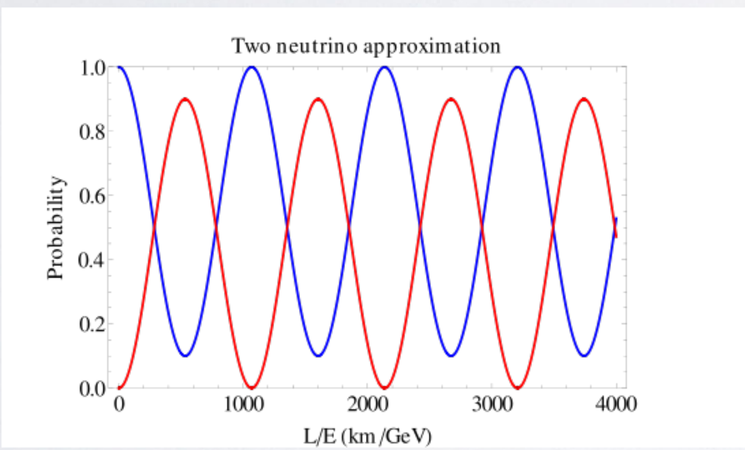


MicroBooNE

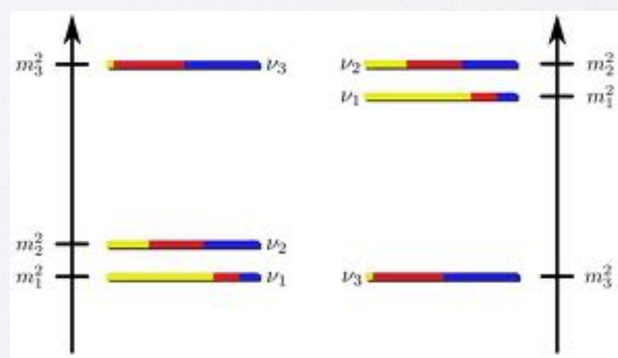
T2K



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

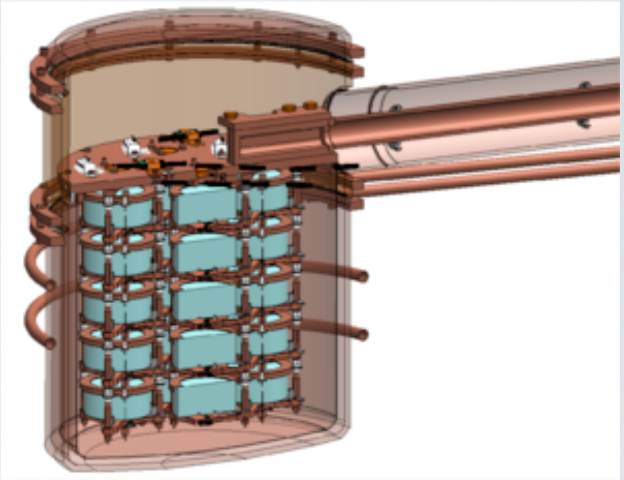
$$
\begin{aligned}
U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \\
&= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0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

Mixing angles, CP violating phases, Majorana Phases

+ MSW effect from forward scattering in matter

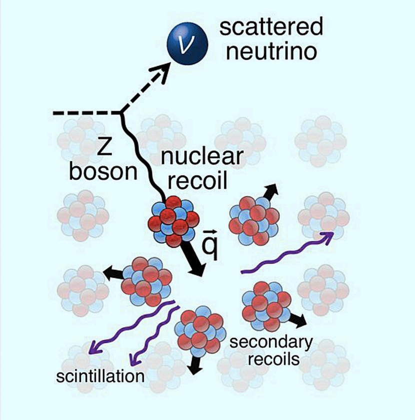
Why study Neutrinos and Nuclei

Double Beta decay
Majorana nature of the neutrino

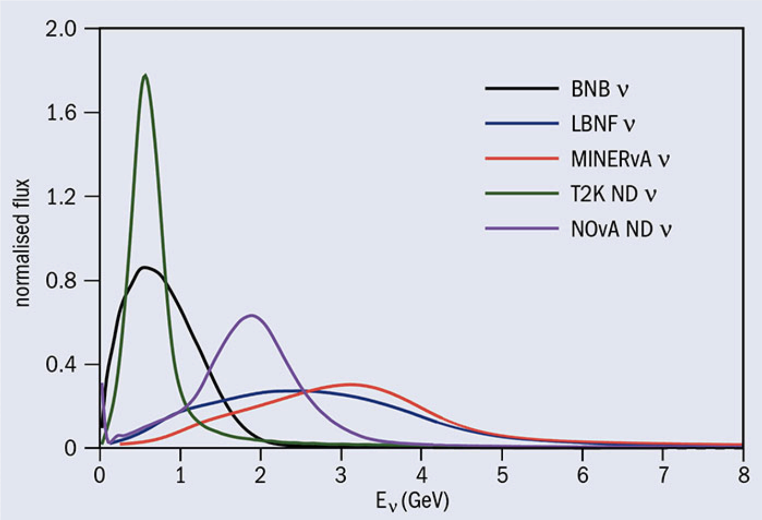


Neutrinos and nuclei are fundamental to some of the largest and most exciting experiments and observations

Coherent neutrino scattering at SNS

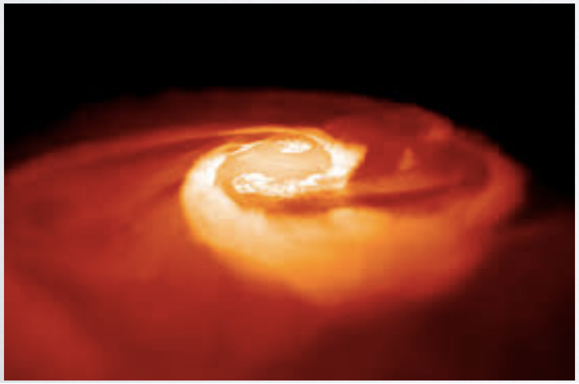


Accelerator Neutrino Measurements:



At high energies resonance and deep inelastic dominate

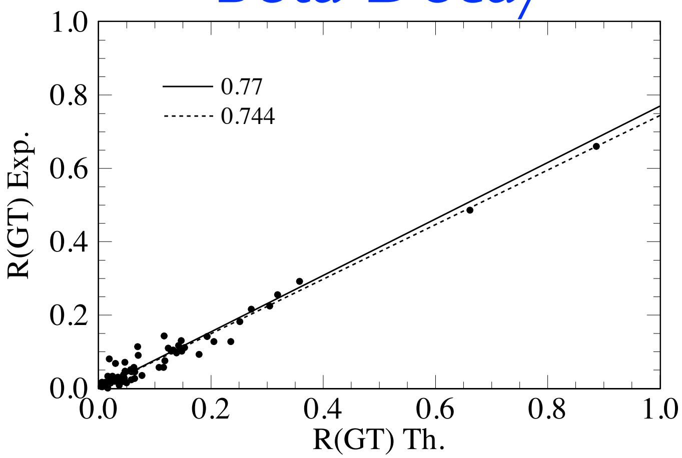
Supernovae/ Neutron star mergers and nucleosynthesis



Recent Theory Status

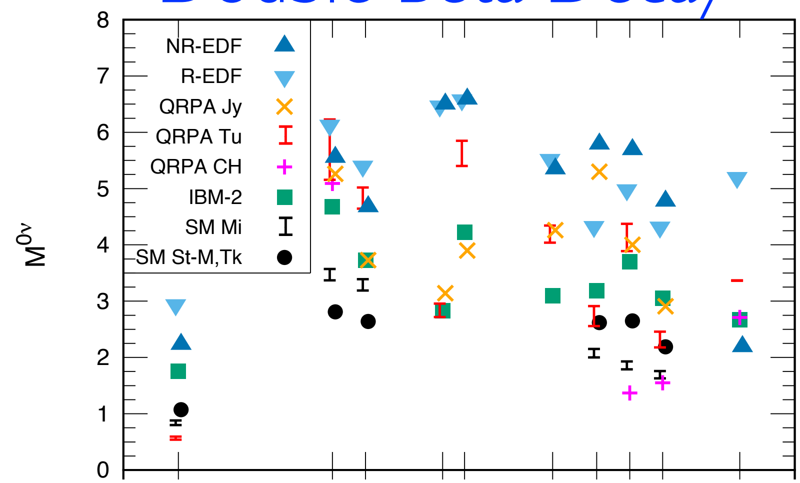
Until recently our understanding of neutrino nucleus interactions has been very limited

Beta Decay



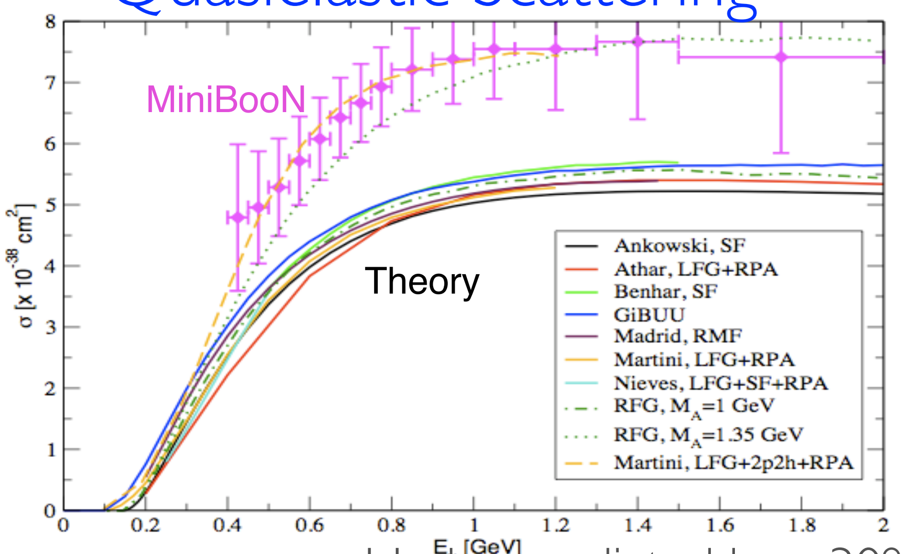
overpredicted: g_A quenching 1.27 ➡ ~1

Double Beta Decay



Factor of >2 uncertainty

Quasielastic Scattering

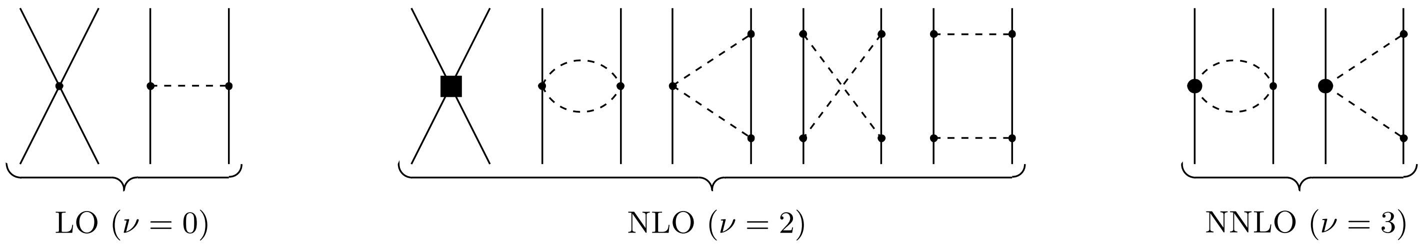


Under predicted by ~30%

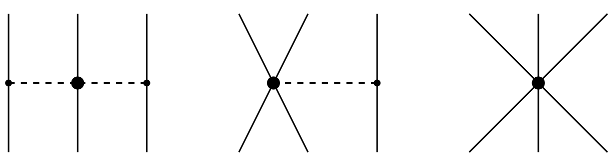
How can we improve our understanding?

Basic building blocks: Nuclear interactions and currents

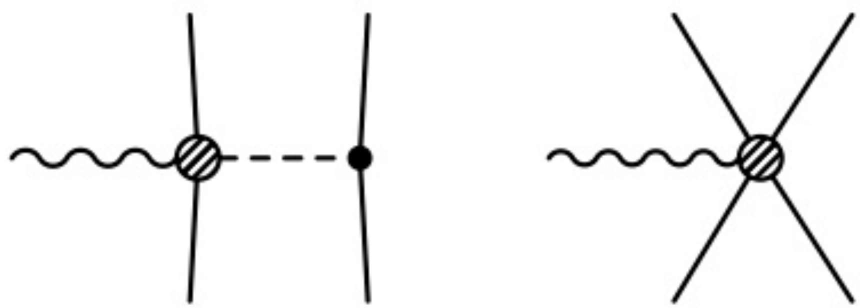
NN interactions



3N interactions



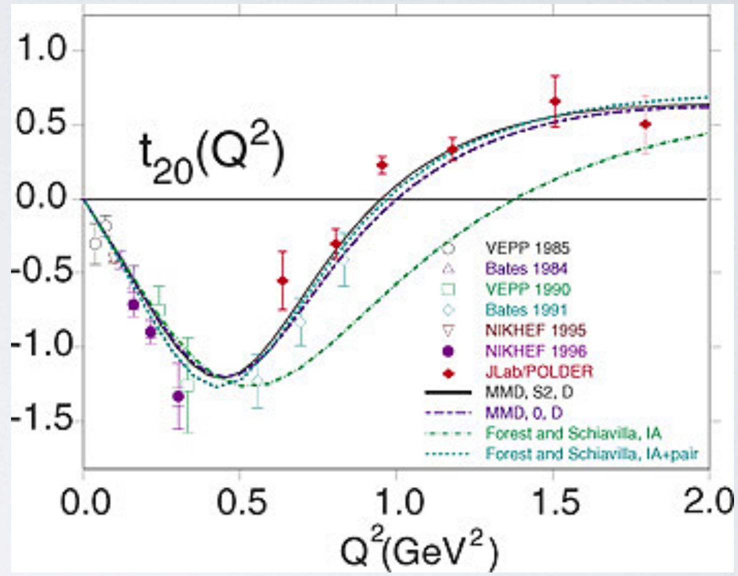
NN currents



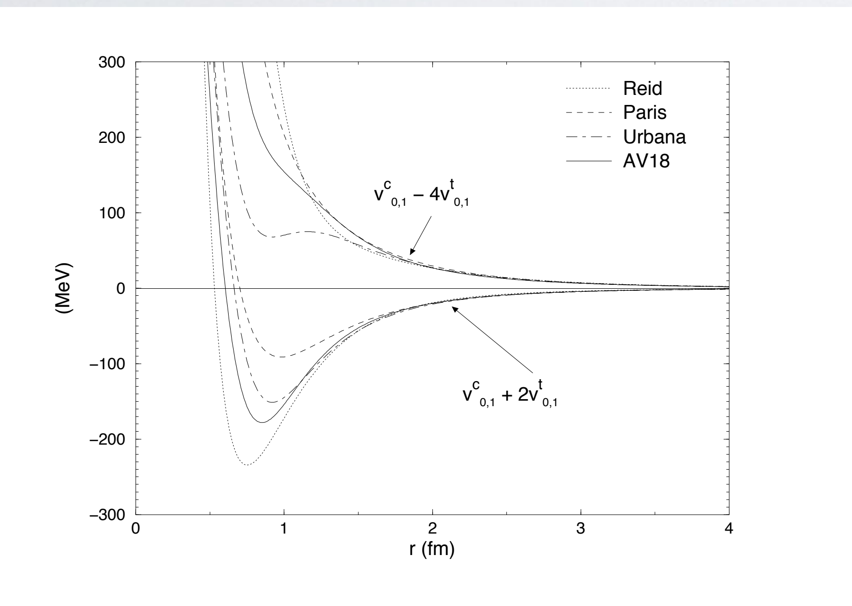
Nuclei: Interactions and Currents

$$H = \frac{1}{2m}\sum_i p_i^2 + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk}$$

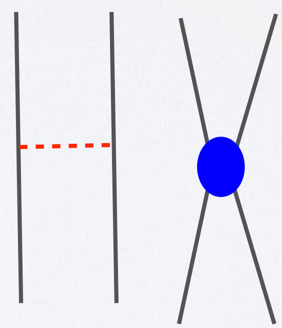
$$\mathbf{J} = \sum_i \mathbf{j}_{1;i} + \sum_{i<j} \mathbf{j}_{\mathbf{2;ij}} + \ldots$$

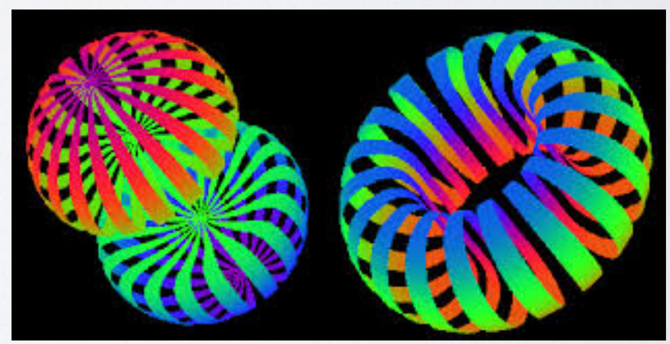


t20 experiment Jlab R. Holt



Deuteron Potential Models with Different Spin Orientations





Forrest, et al, PRC 1996

^{12}C calculations:

NUCLEI
Nuclear Computational Low-Energy Initiative

computingnuclei.org

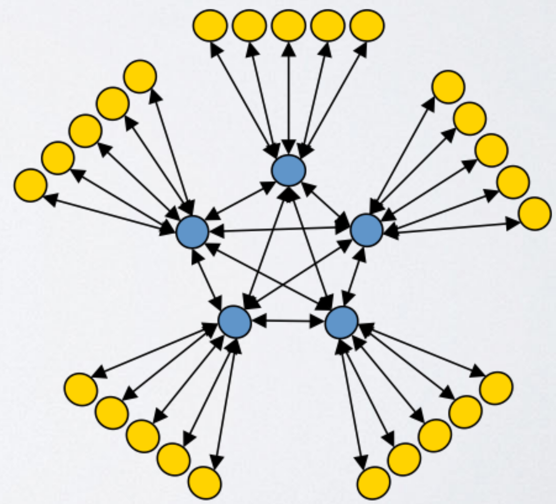
GFMC for ground-state
+ current correlation matrix elements

$$\Psi_0 \ = \exp\left[-H\tau\right]\, \Psi_T$$

2^A = 4096 spin amplitudes x
12!/(6!6!) = 924 isospin amplitudes
(charge basis) for each sample

~ 45 M core-hours

ADLB
Lusk, Pieper, …



SciDAC
Scientific Discovery through Advanced Computing

U.S. DEPARTMENT OF ENERGY | Office of Science

U.S. DEPARTMENT OF ENERGY
INCITE
LEADERSHIP COMPUTING

NNSA
National Nuclear Security Administration

http://www.mcs.anl.gov/project/adlb-asynchronous-dynamic-load-balancer

Light Nuclear Spectra

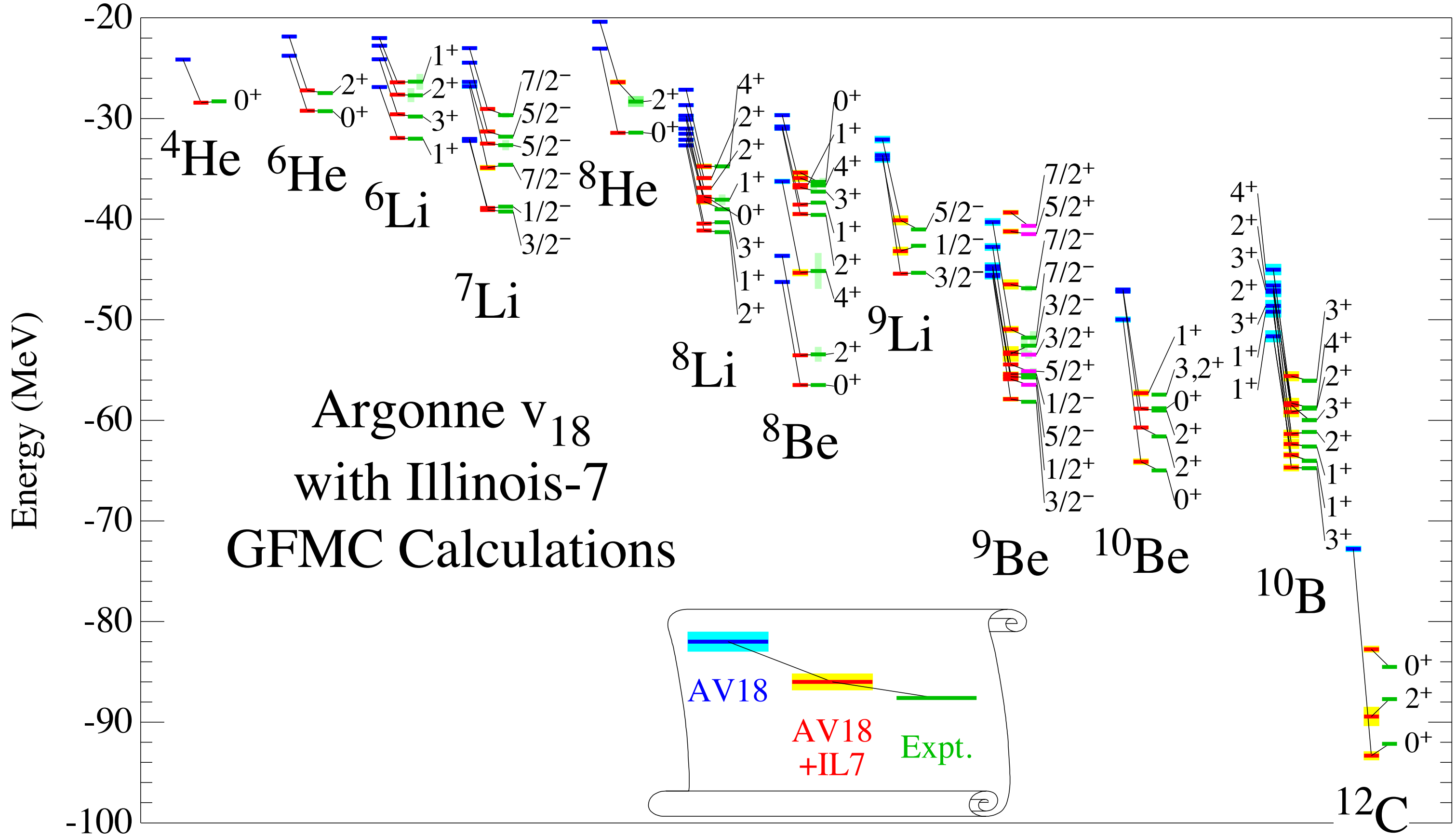
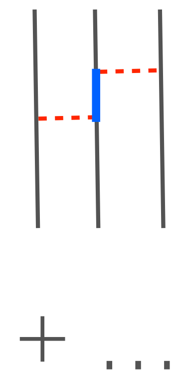
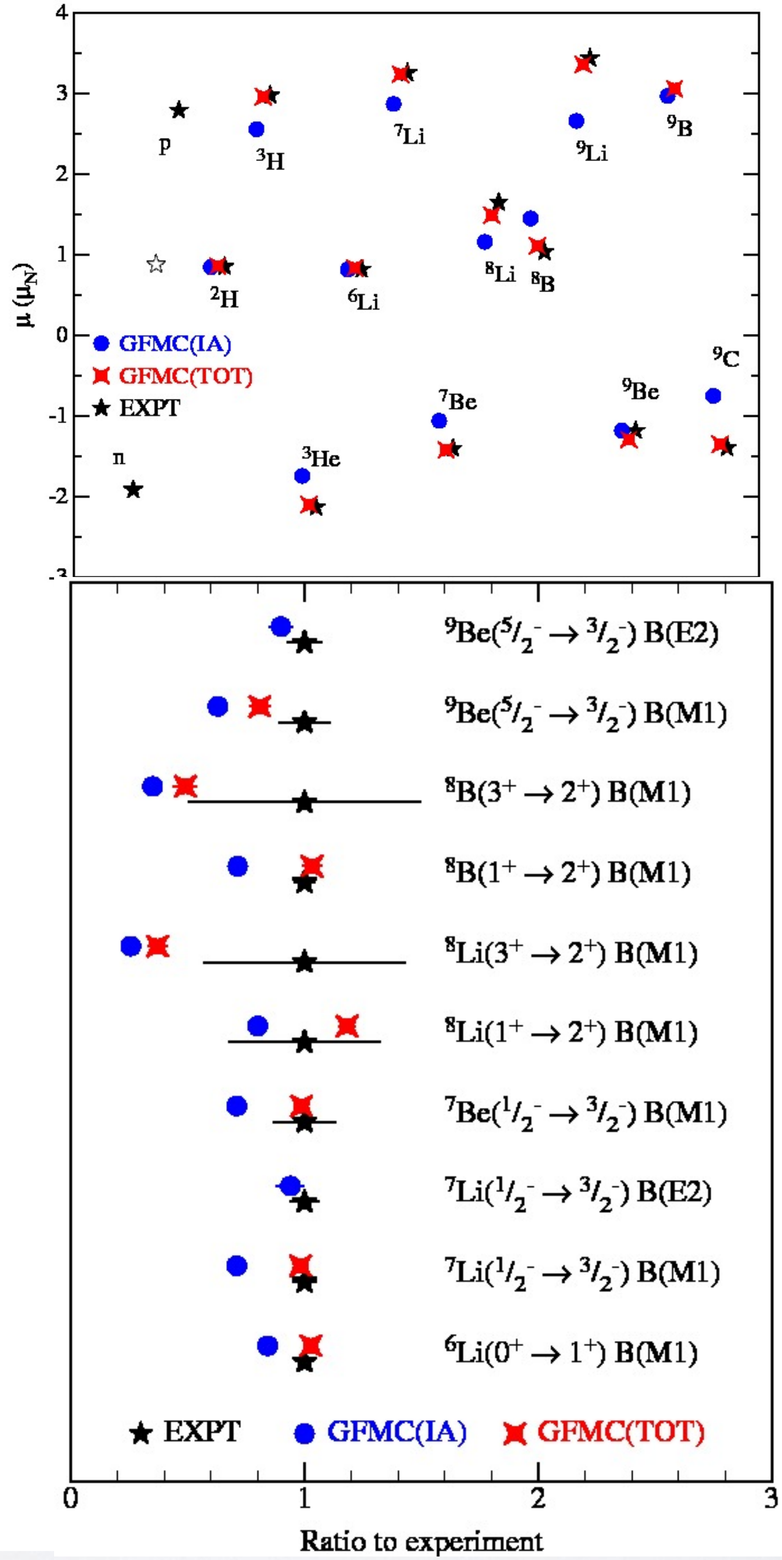


FIG. 2 GFMC energies of light nuclear ground and excited states for the AV18 and AV18+IL7 Hamiltonians compared to experiment.

Carlson, et al, RMP 2015



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



Magnetic Moments

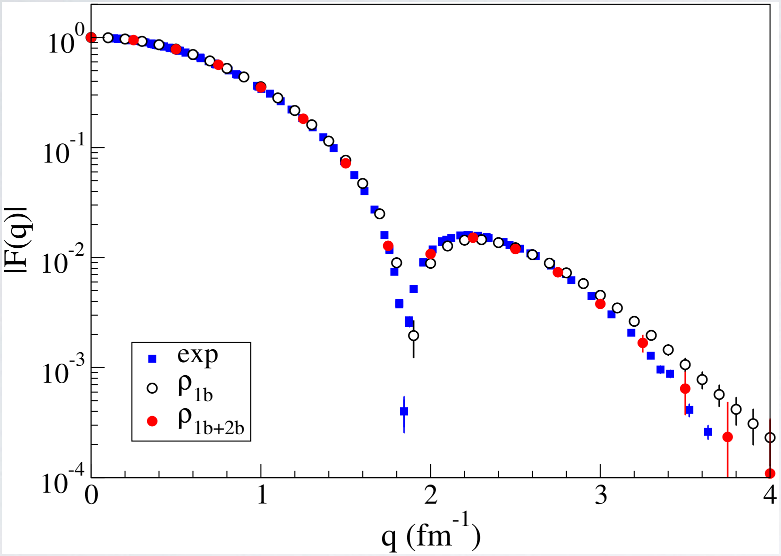
EM Transitions

Wiringa, Pastore, Schiavilla, et al

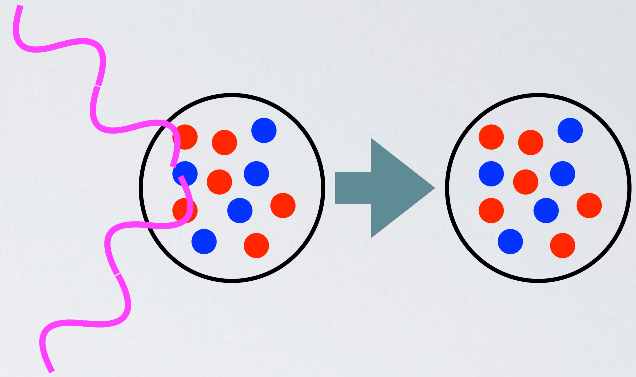
NUCLEI
Nuclear Computational Low-Energy Initiative

Electromagnetic form factors

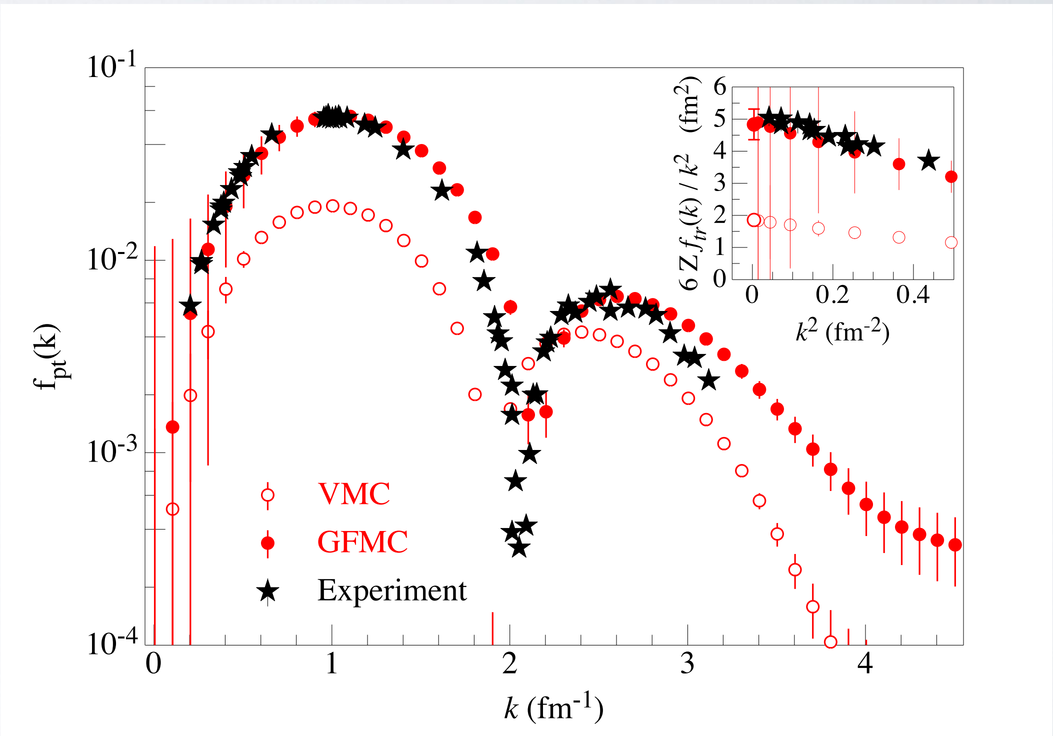
^{12}C elastic form factor



2 Nucleon charge operators (relativistic corrections) are small



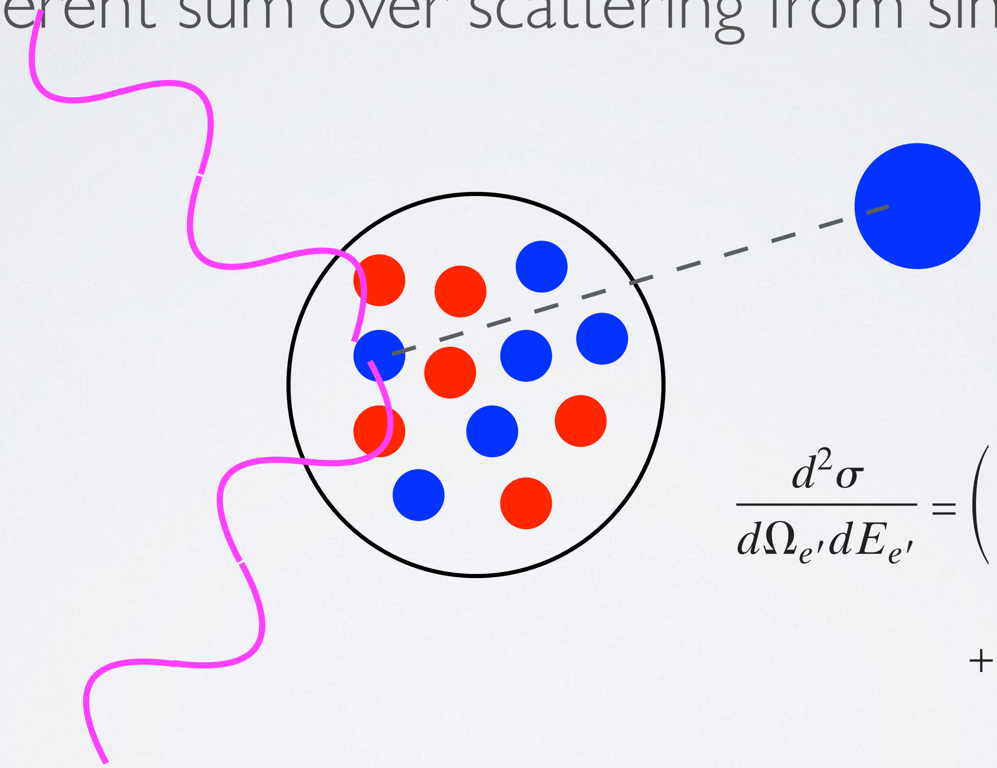
Hoyle state transition form factor



NUCLEI
Nuclear Computational Low-Energy Initiative

Quasi-elastic scattering: higher p, E

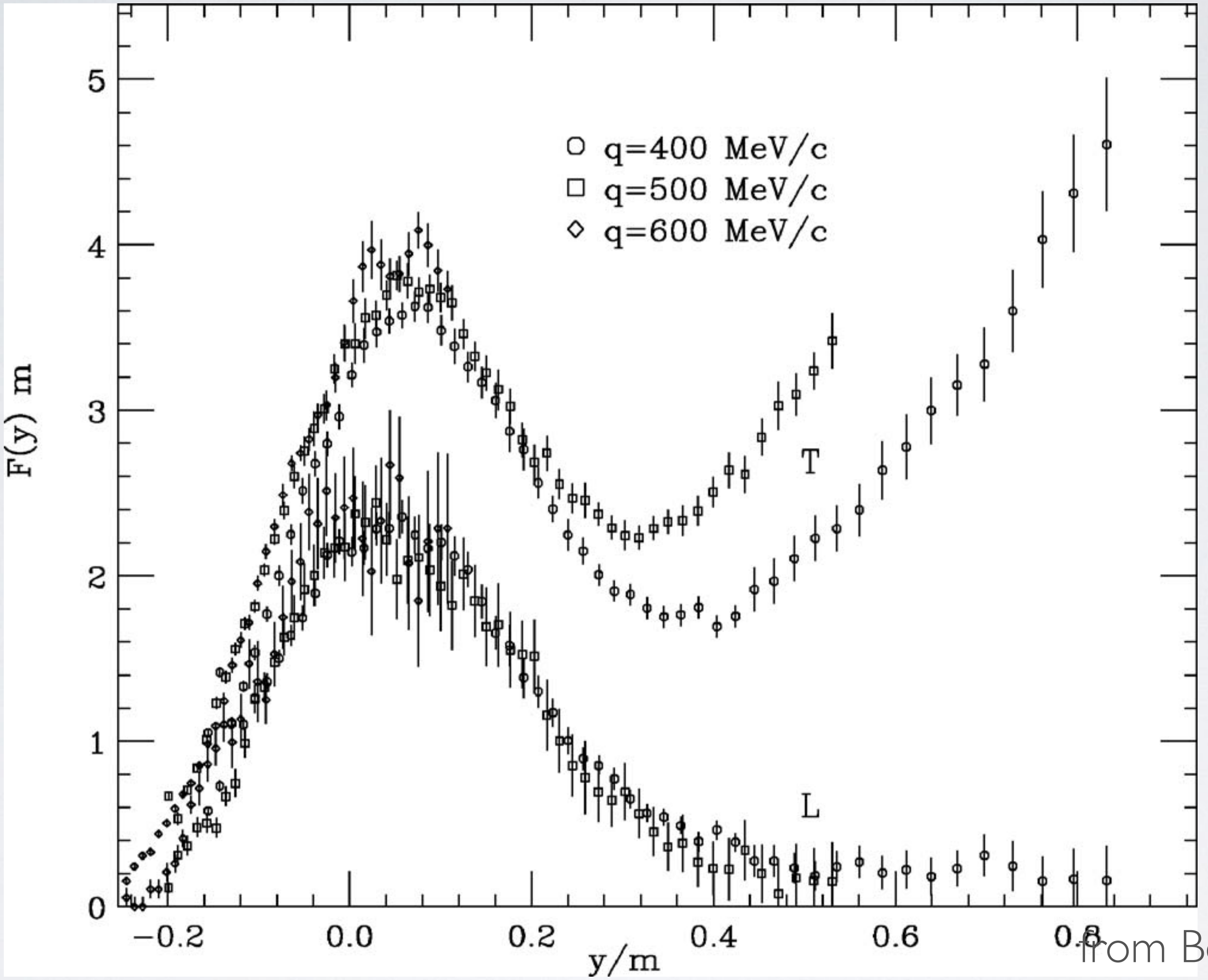
Scaling with momentum transfer: 'y'-scaling
incoherent sum over scattering from single nucleons



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

PWIA often good for q >> k_F; used in many fields
(neutron scattering, …)

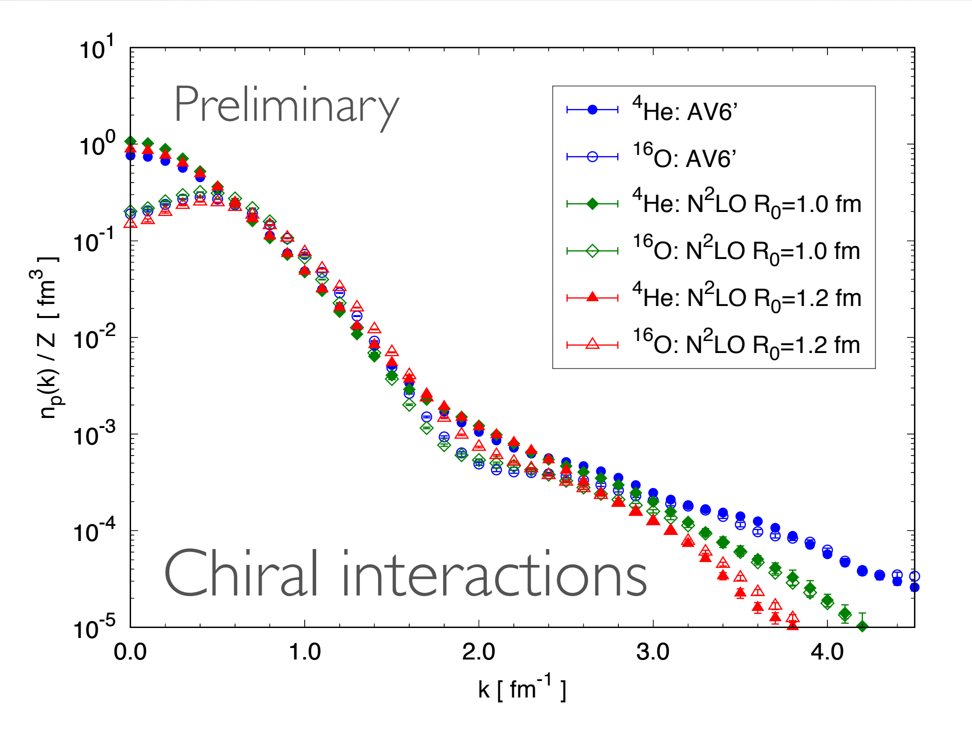
Quasi-Elastic electron scattering:
^{12}C transverse/longitudinal response

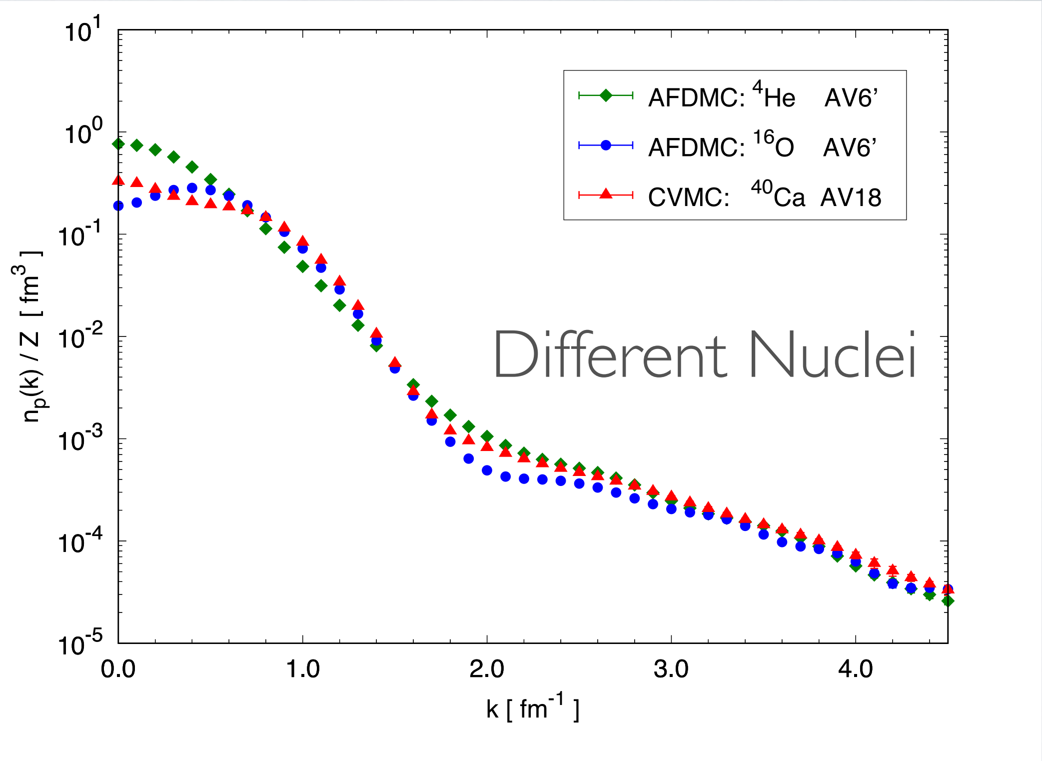


from Benhar, Day, Sick, RMP 2008
data Finn, et al 1984

Scaled longitudinal vs. transverse scattering from 12C

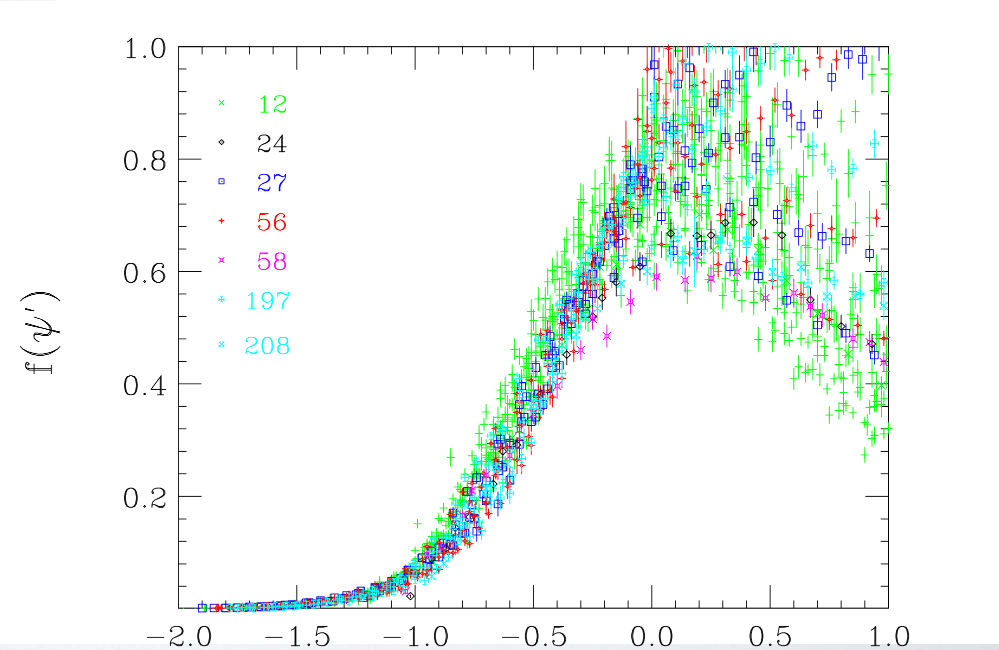
Single-Nucleon Momentum Distributions





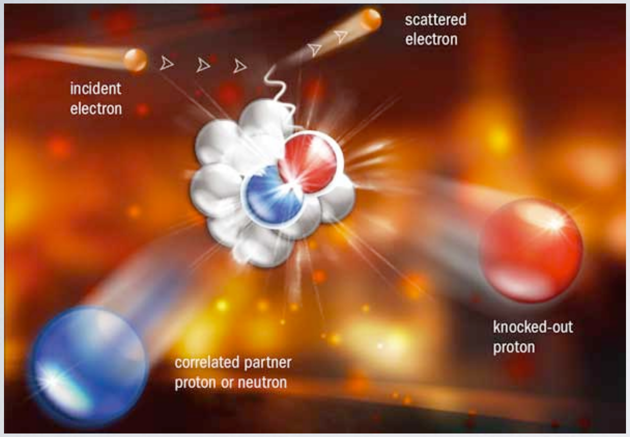
Lonardoni, Gandolfi, Wiringa, Pieper, et al

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



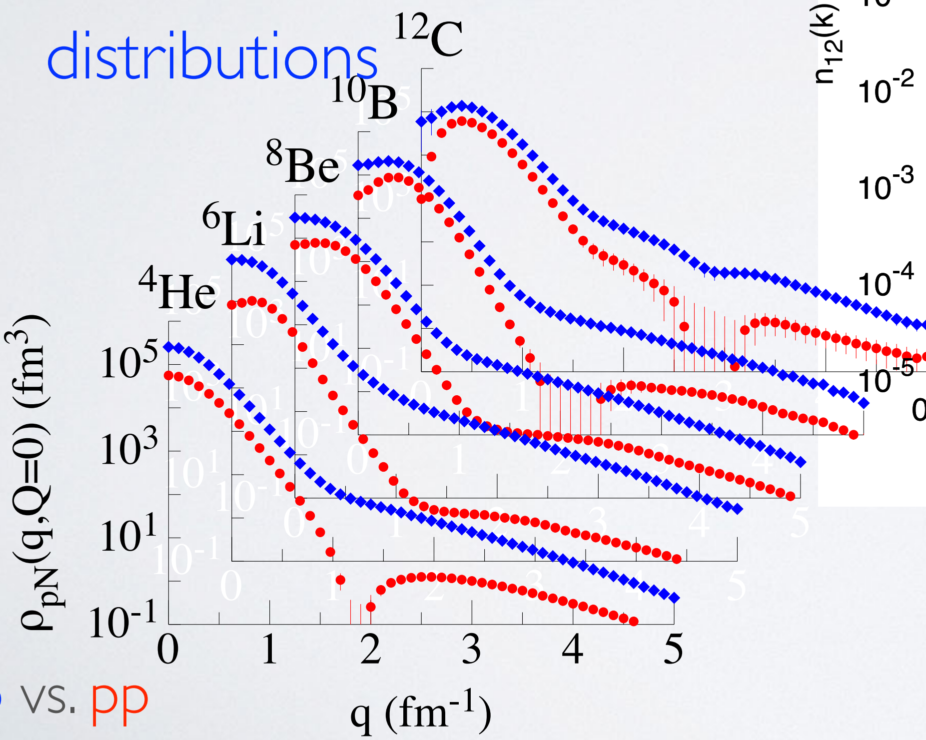
Scaling of the 1st kind (w/ p)
Donnelly & Sick (1999)

Back to Back Nucleons (total Q~0)
np pairs dominate over nn and pp



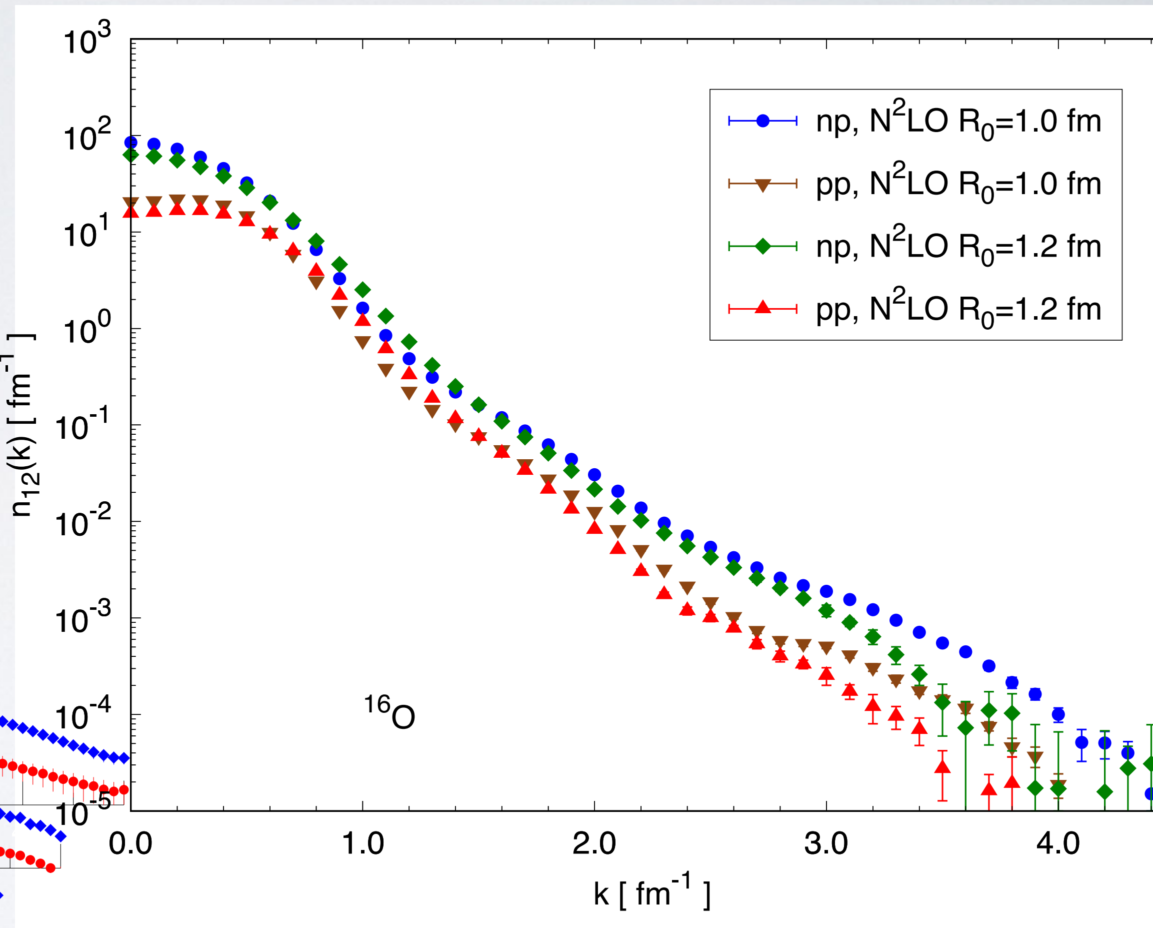
E Piasetzky *et al.* 2006 **Phys. Rev. Lett. 97** 162504.
M Sargsian *et al.* 2005 **Phys. Rev. C 71** 044615.
R Schiavilla *et al.* 2007 **Phys. Rev. Lett. 98** 132501.
R Subedi *et al.* 2008 **Science 320** 1475.

2-nucleon momentum distributions



np vs. pp

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



Lonardoni, et al, preliminary

Electron Scattering:
Longitudinal and Transverse Response

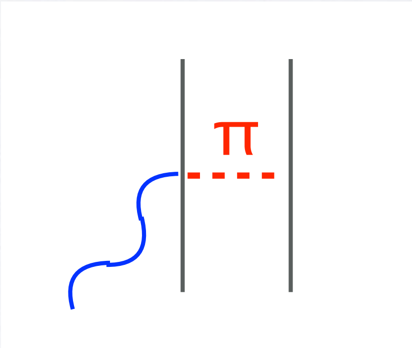
Transverse (current) response:

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

Longitudinal (charge) response:

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

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



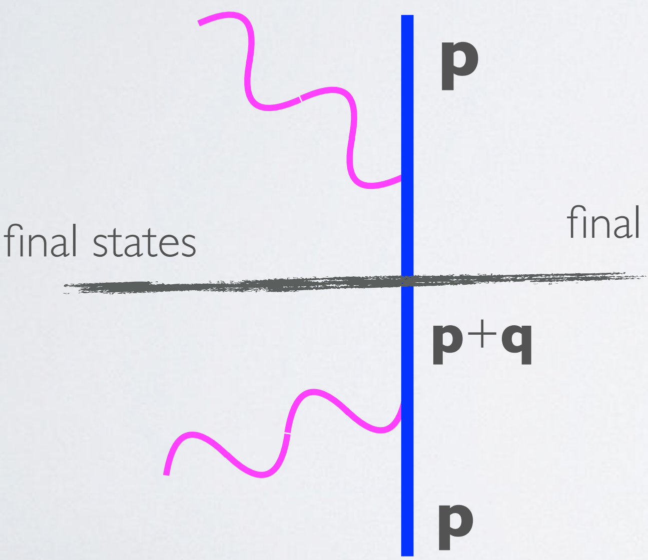
Two-nucleon currents required by current conservation
Response depends upon all the excited states of the nucleus

Sum Rules: Longitudinal Response

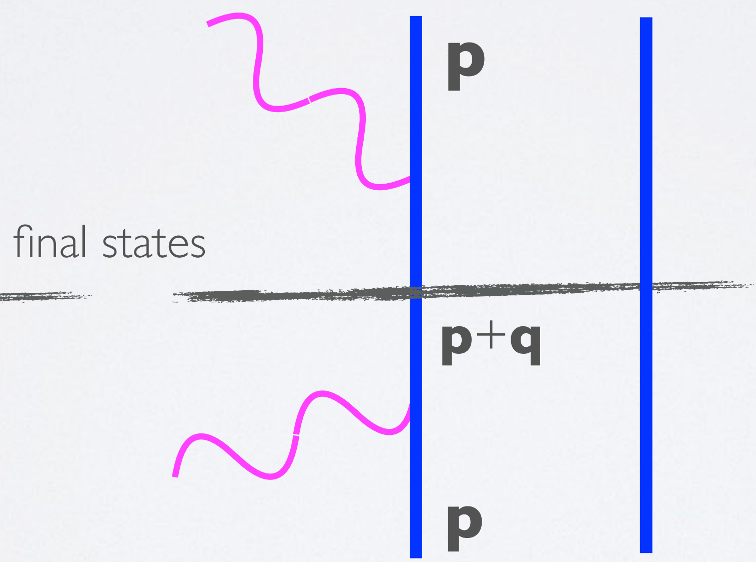
$$S\ (q)\ =\ \langle\ 0\ |\ \mathbf{j}^\dagger(q)\ \mathbf{j}(q)\ 0\ \rangle$$

Gives an indication of total strength,
but not energy dependence

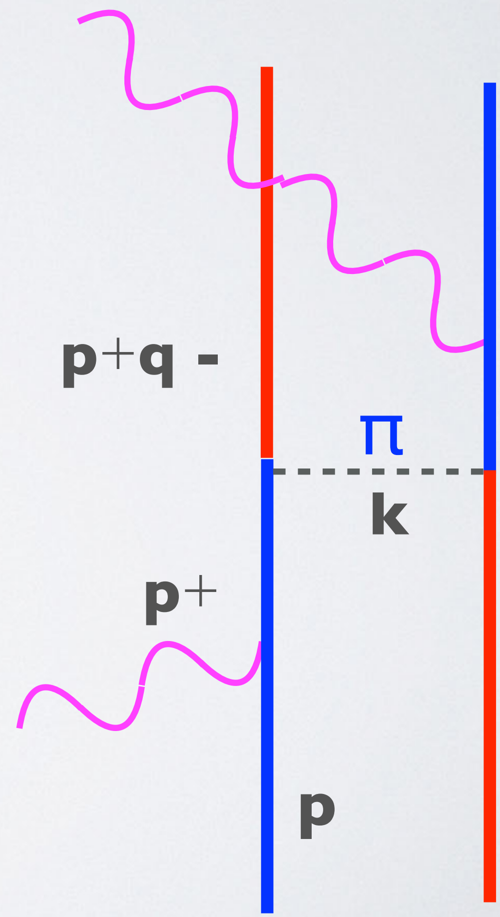
PWIA



Sum Rule
determined by
pp correlations

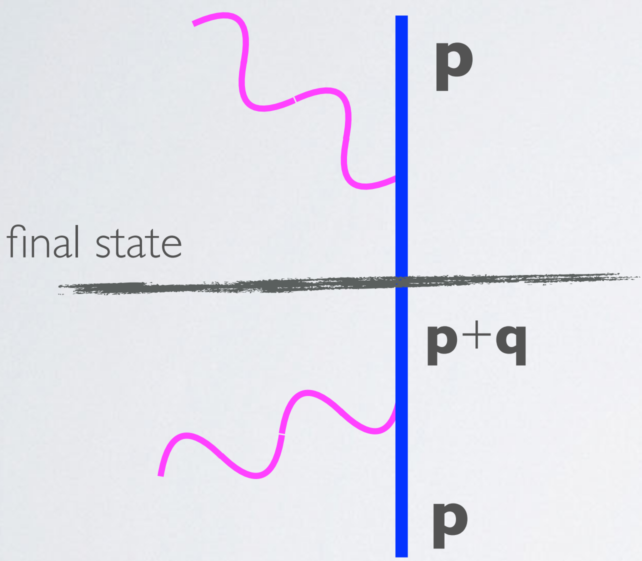


Energy dependence
pion exchange
final state interaction

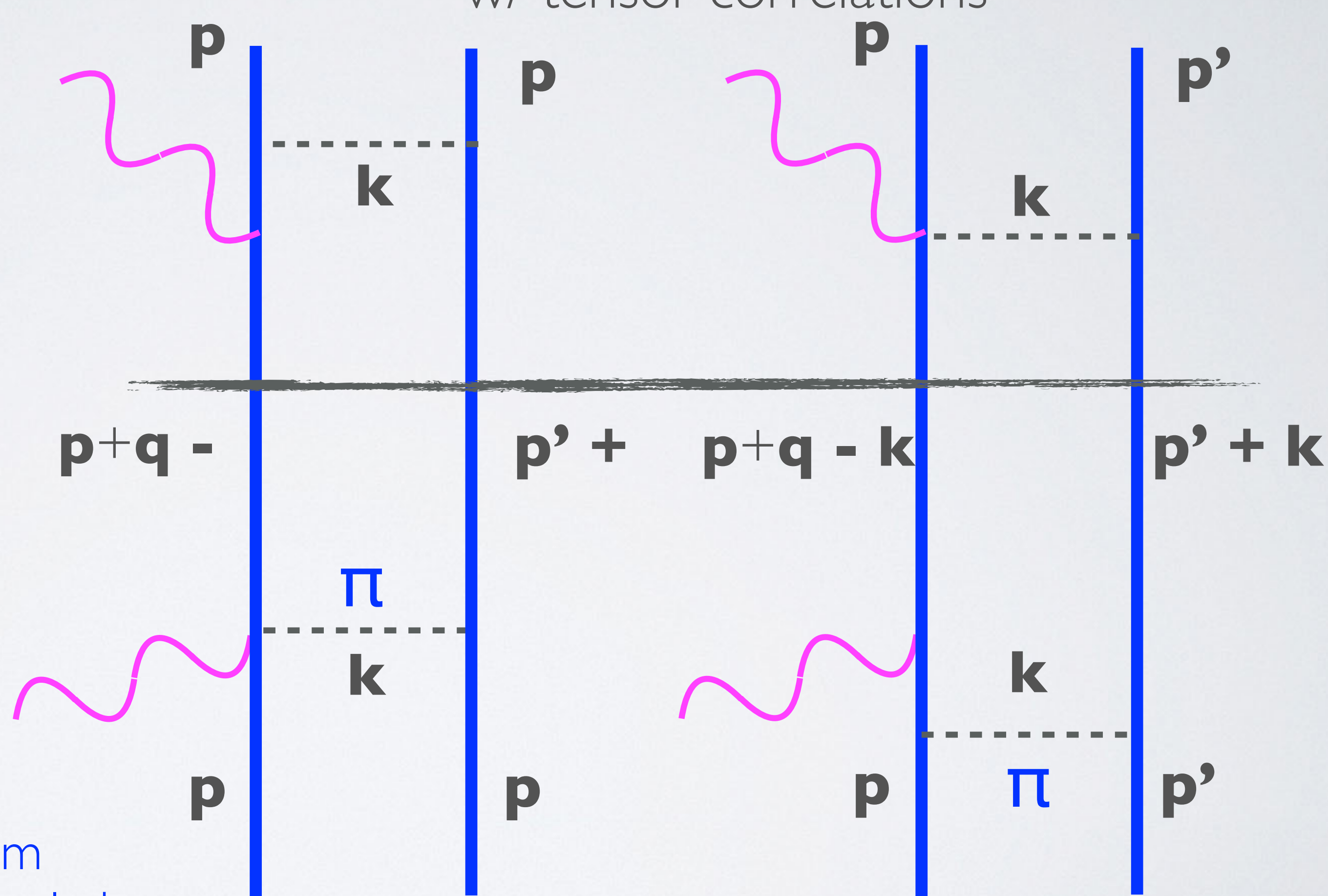


Vector Response

PWIA



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



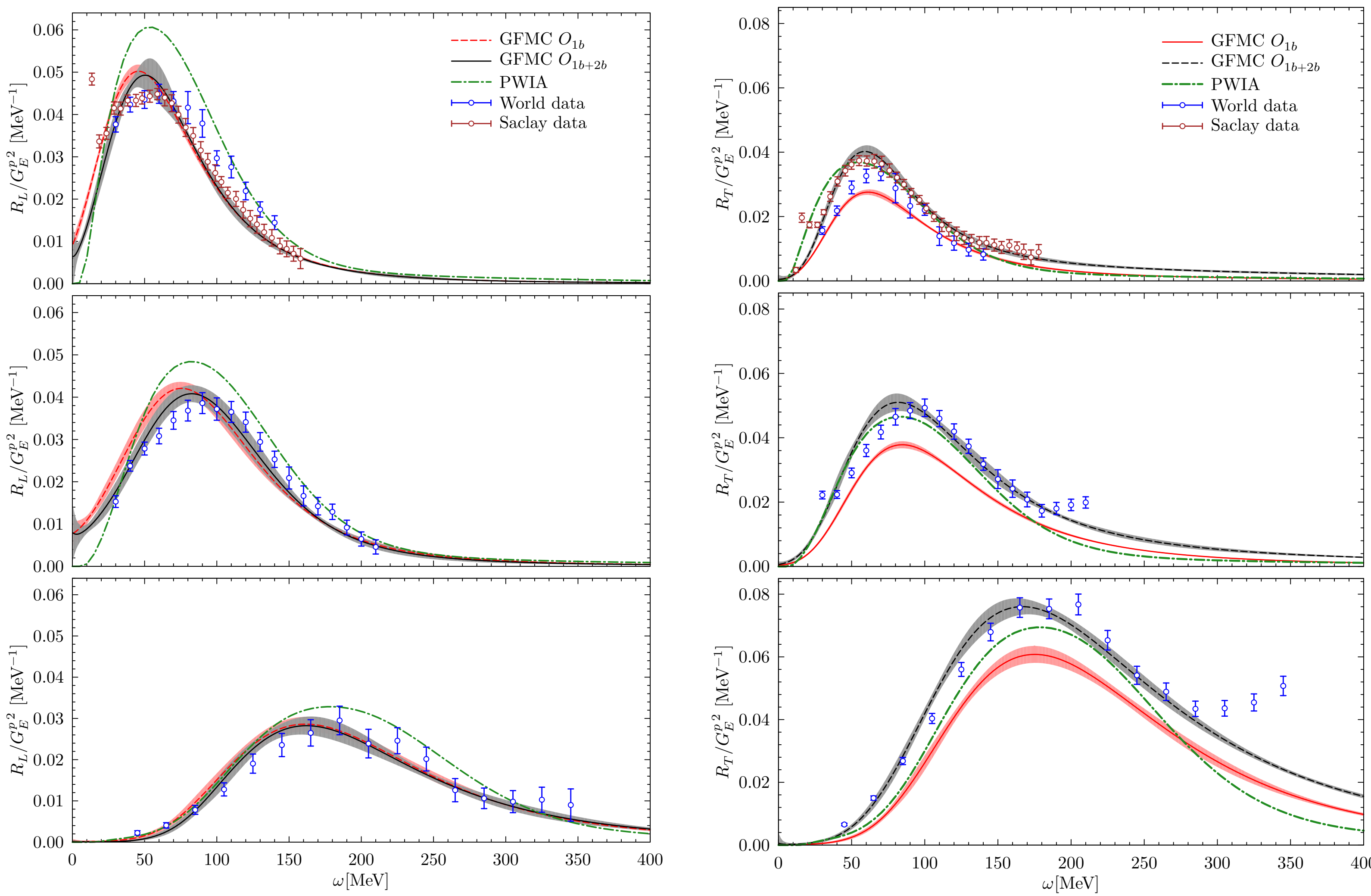
Large enhancement from combination of initial state correlations and two-nucleon currents similar in axial response

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

^{12}C EM response

Longitudinal

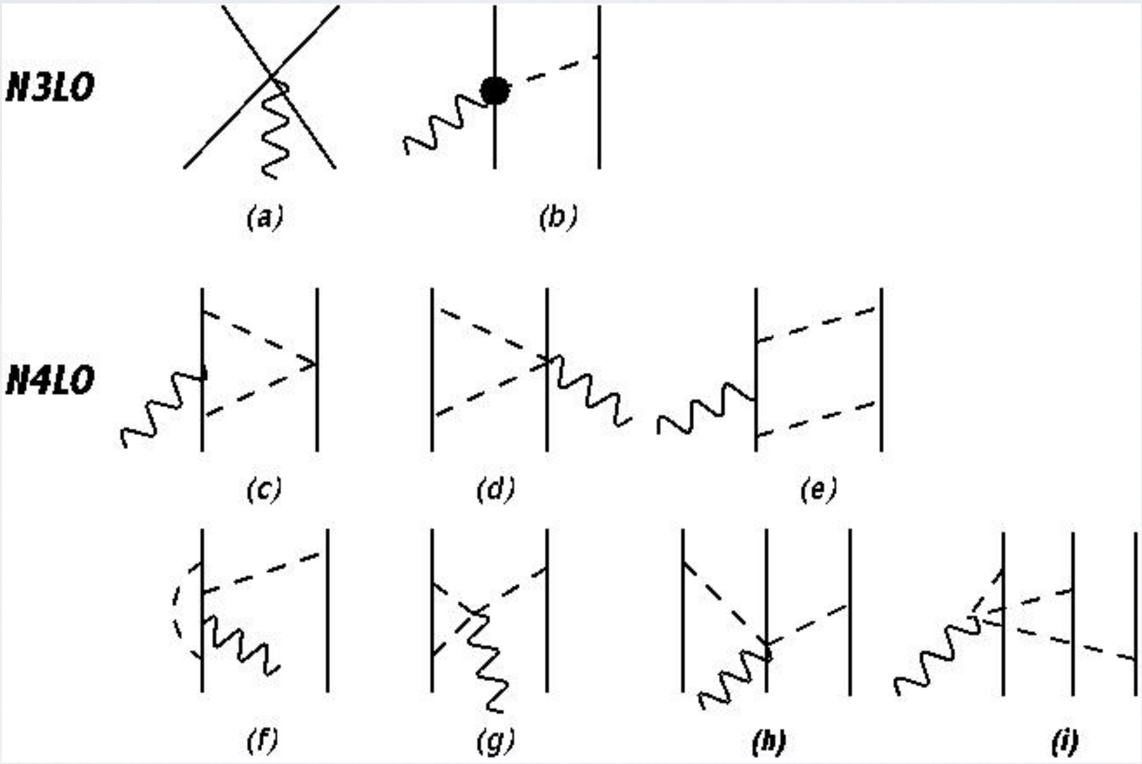
Transverse



Lovato, et al, PRL, 2016

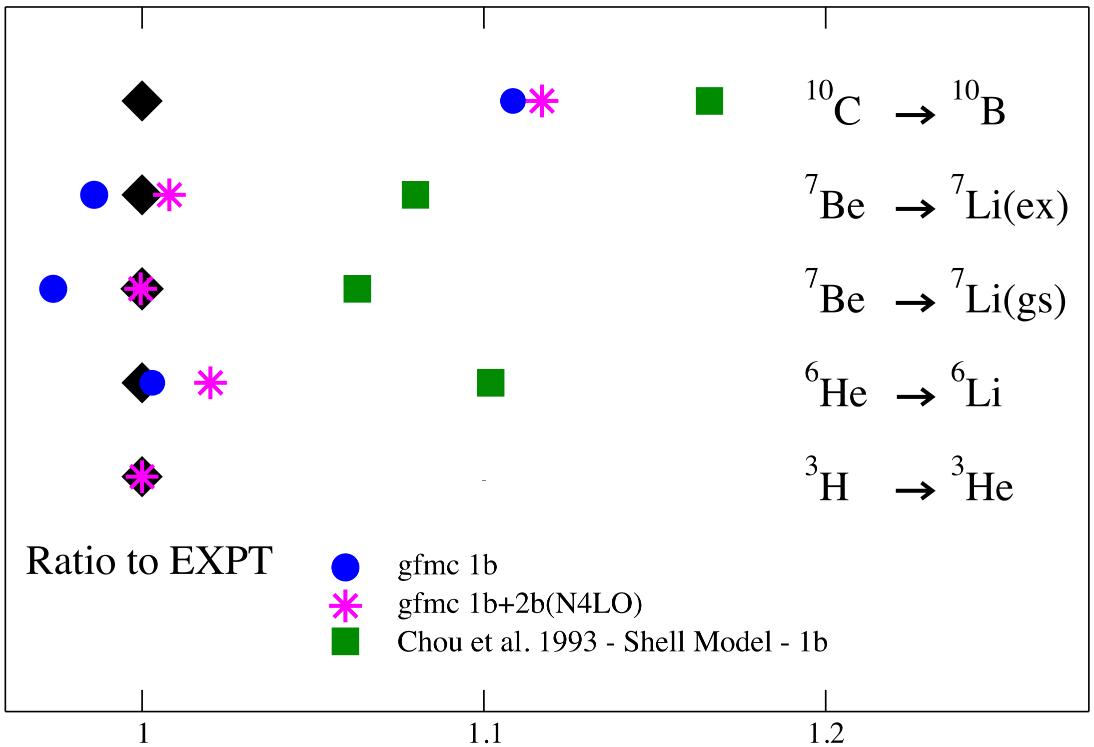
EM observables well-reproduced

What about neutrinos and weak currents?



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

Beta Decay in Light Nuclei

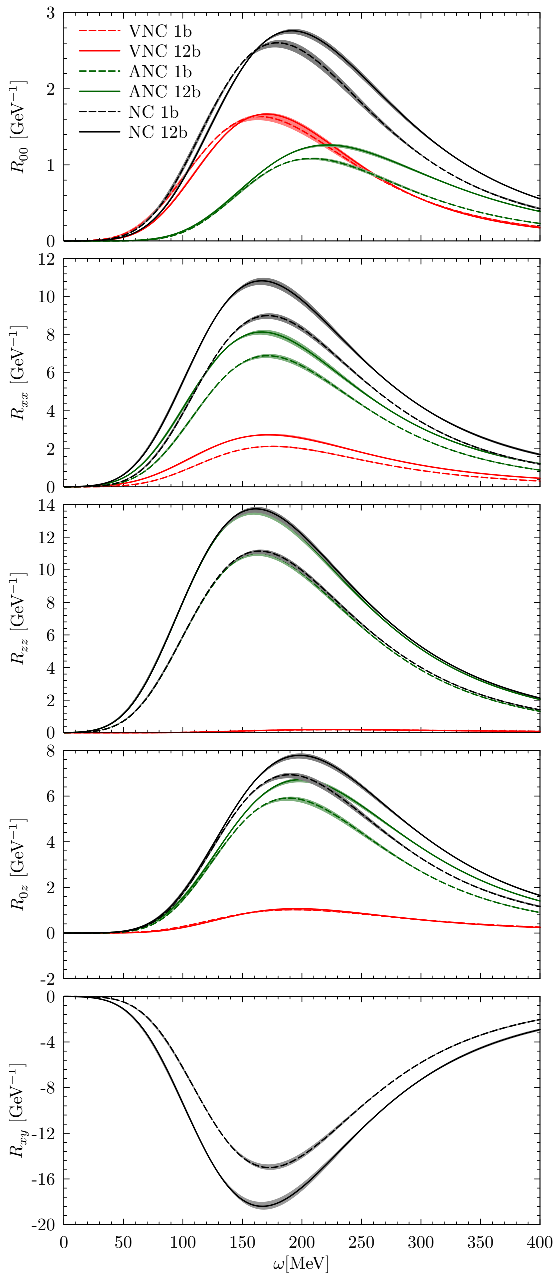


- Contact fit to Tritium beta decay
- Substantial reduction due to two-body correlations
- Modest 2N current contribution
- Good description of experimental data, explains ‘quenching’
- Many calculations with larger nuclei underway

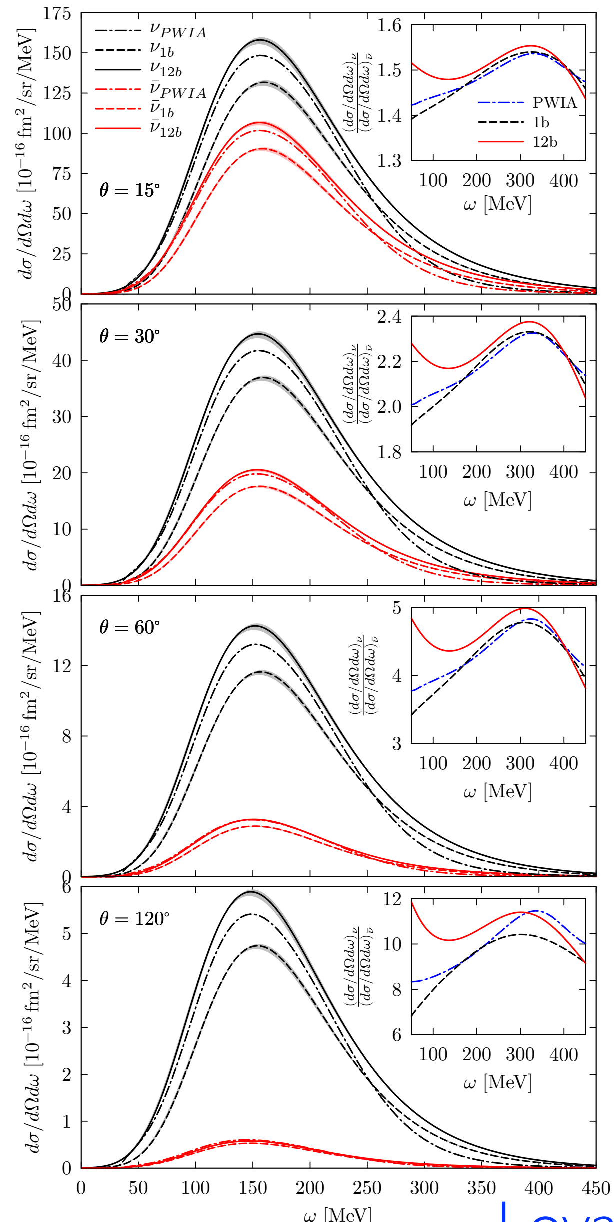
Neutral Current Response/Cross Sections 12C

Response functions

Vector
Axial
Total



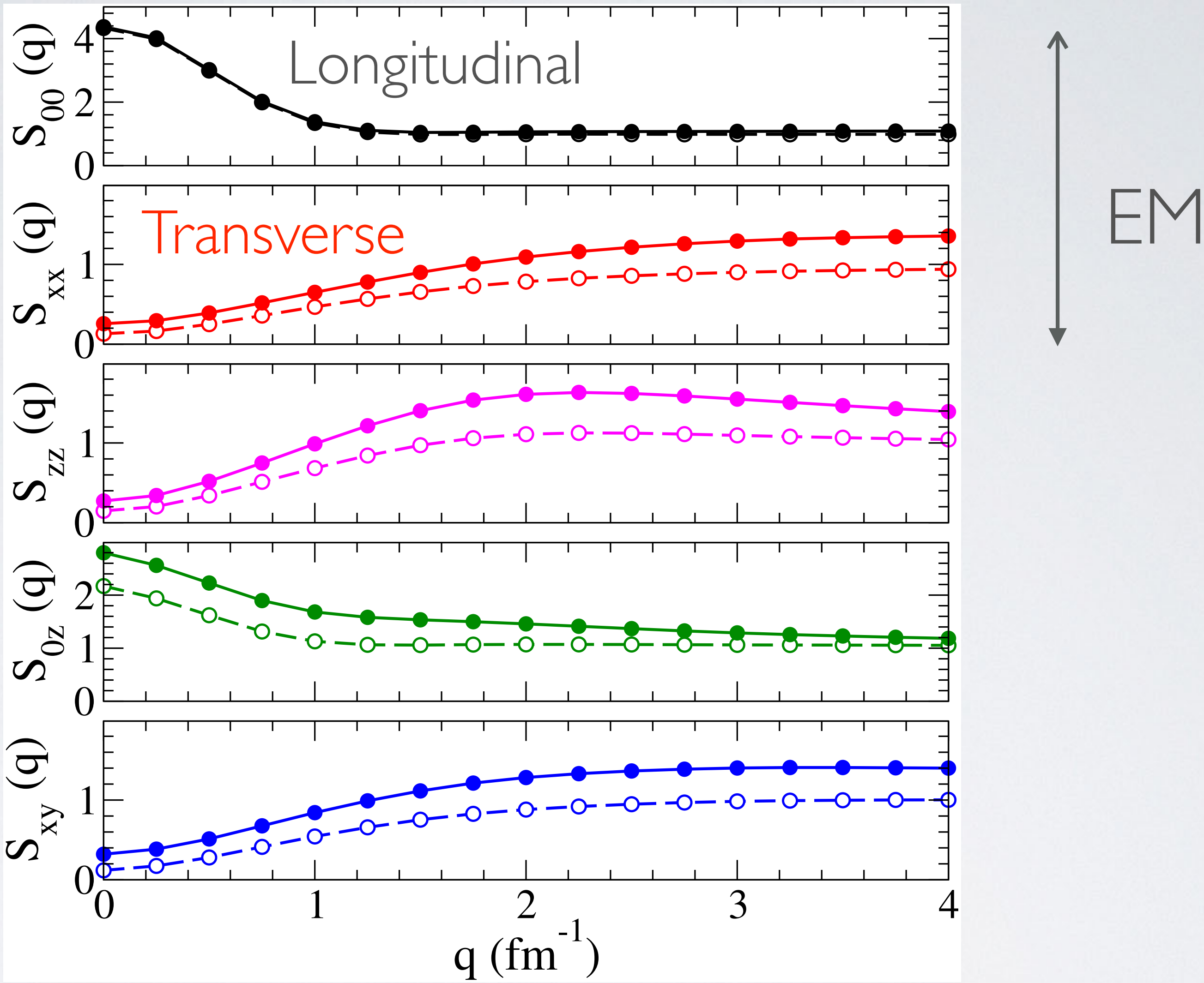
Cross sections



anti-ν
ν

Lovato, et al, 2017

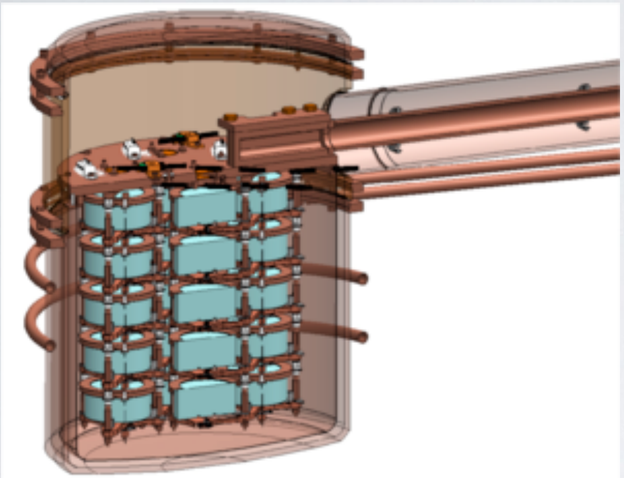
Sum rules in ^{12}C: neutral current scattering



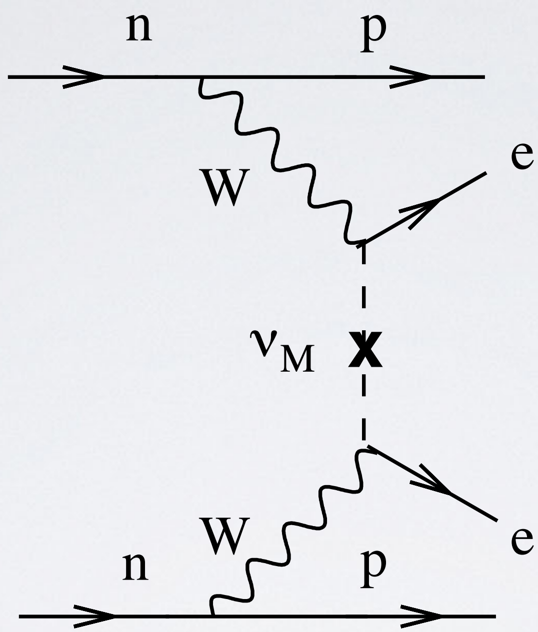
Lovato, et. al PRL 2014

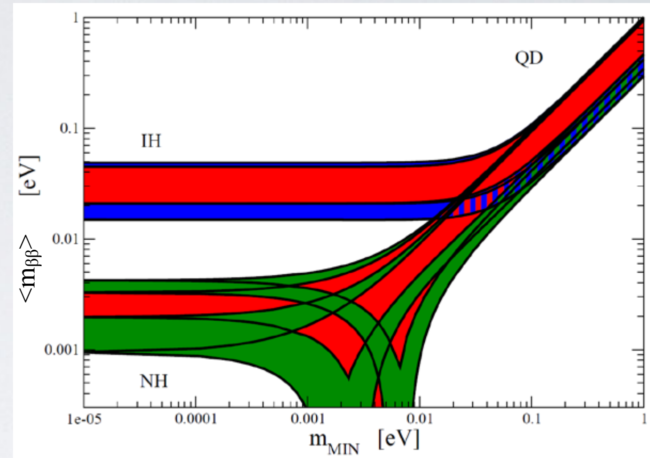
Single Nucleon currents (open symbols) versus
Full currents (filled symbols)

Quenching in beta decay and Enhancement in QE scattering What about double beta decay?



Majorana





$$\langle m_{\beta\beta} \rangle = \sum_i U_{ei}^2 m_i$$

$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2\,\langle m_{\beta\beta}\rangle^2$$

Matrix Element for light Majorana neutrino exchange)

$$M_{0\nu} = g_A^2\; M_{0\nu}^{GT} - g_V^2 M_{0V}^F$$

$$M_{0V}^{GT} = \langle f| \sum_{i<j} \frac{R}{r} \sigma_i \cdot \sigma_j \; \tau_i^+ \tau_j^+ |i\rangle$$

$$M_{0V}^{F} = \langle f| \sum_{i<j} \frac{R}{r} \; \tau_i^+ \tau_j^+ |i\rangle$$

Rate goes like $g_A{}^4$

Double Beta Decay Matrix Element
(light Majorana neutrino exchange)

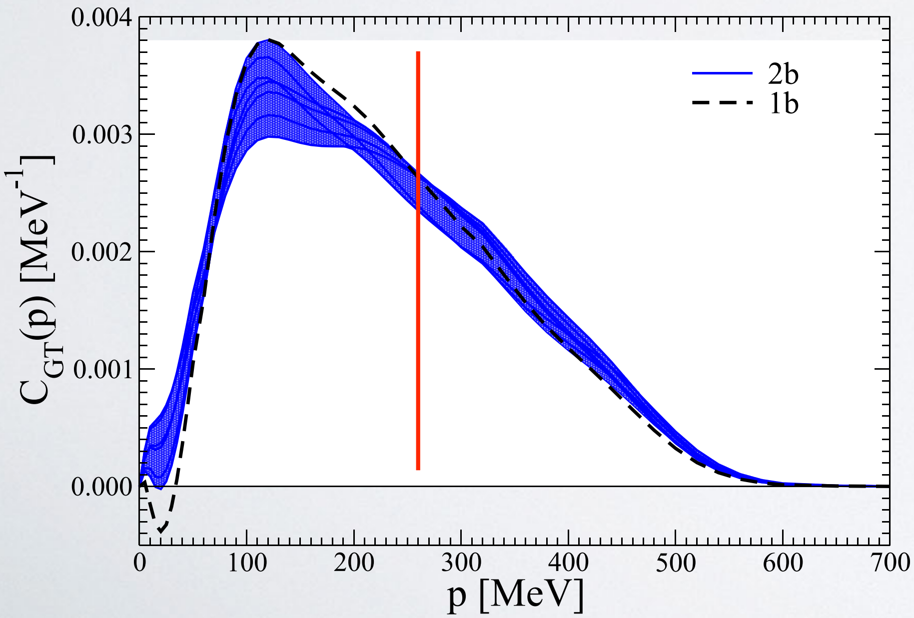
$$M_{0\nu} = g_A^2 \; M_{0\nu}^{GT} - g_V^2 M_{0V}^{F}$$

$$M_{0V}^{GT} = \langle f | \sum_{i<j} \frac{R}{r} \sigma_i \cdot \sigma_j \; \tau_i^+ \tau_j^+ | i \rangle$$

$$M_{0V}^{F} = \langle f | \sum_{i<j} \frac{R}{r} \; \tau_i^+ \tau_j^+ | i \rangle$$

corrections from two-nucleon currents, quenching of g_A?

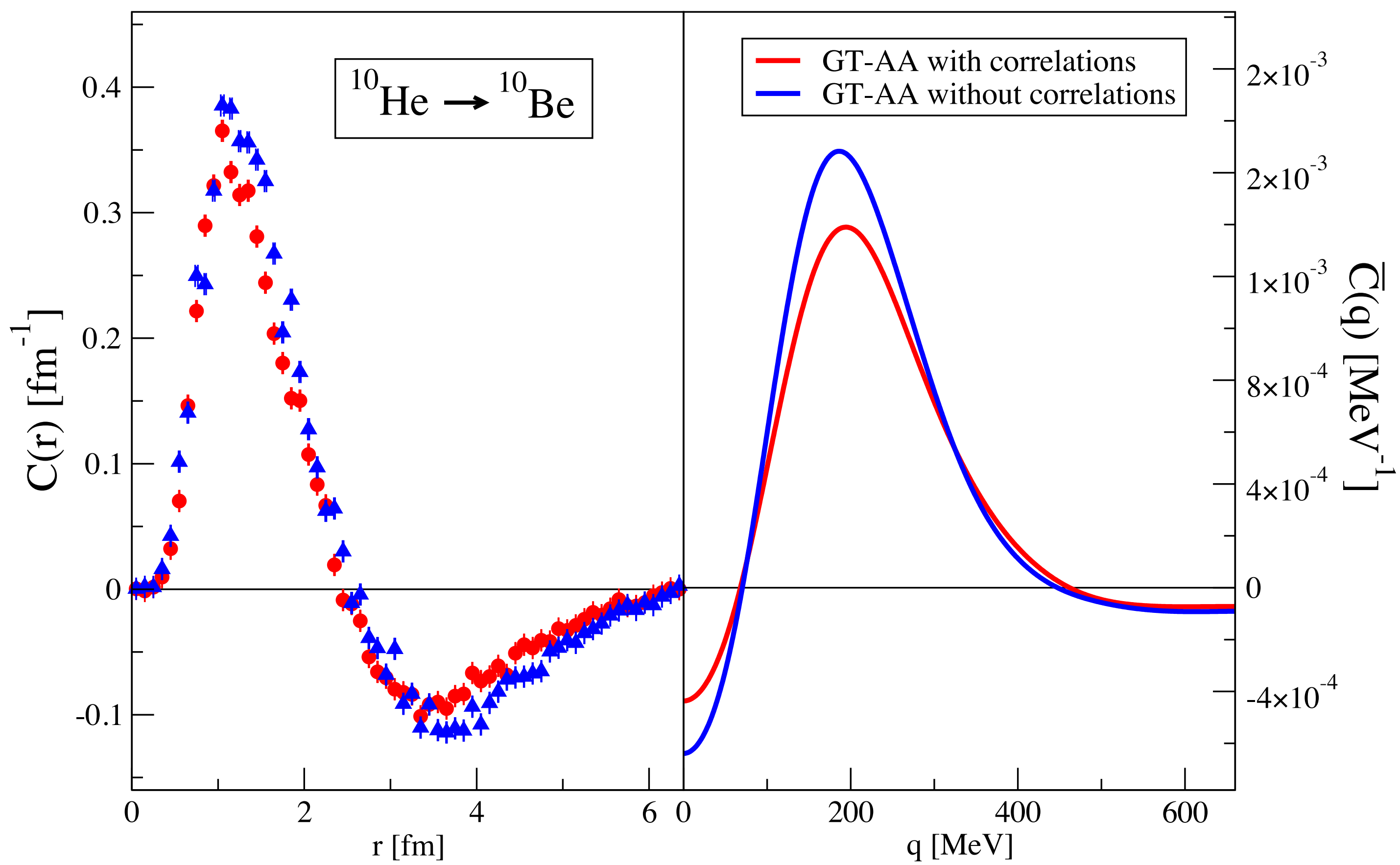
MC methods sum over all intermediate states



Different from single-beta decay and from inclusive scattering

Engel, Simkovic Vogel (2014)

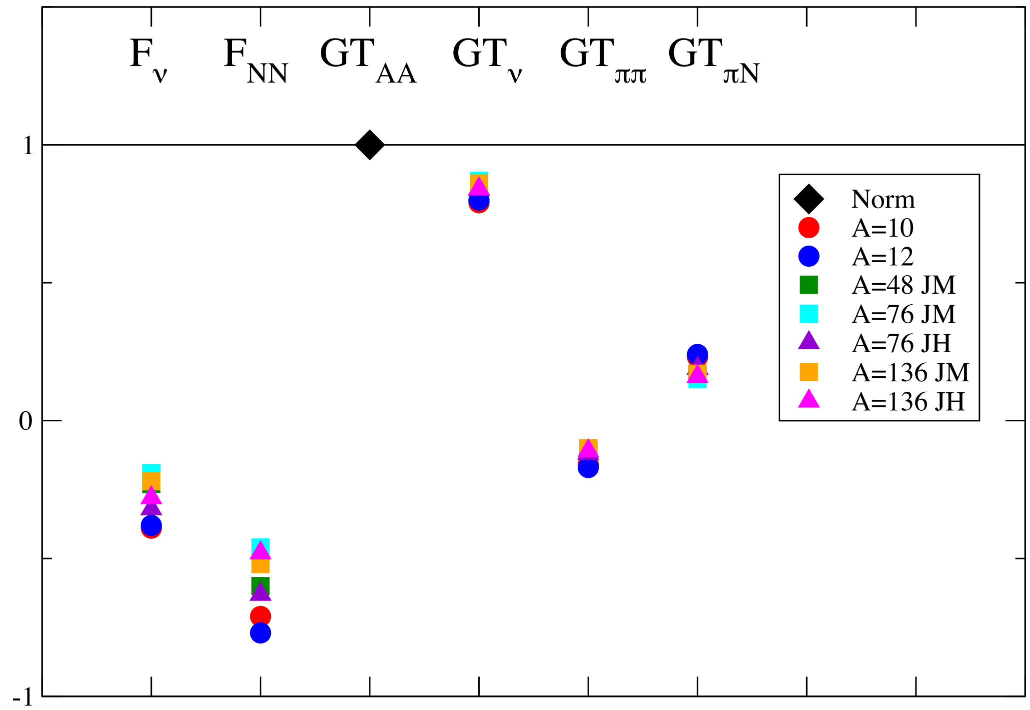
Double Beta Decay ME in light Nuclei



Pastore, et al, 2017

Double Beta Decay ME in light Nuclei

Includes possible short-range contributions



JM = Javier Menendez private communication
JH = Hyvärien *et al.* PRC91(2015)024613

* Relative size of the matrix elements is approximately the same in all nuclei
* Short-range terms approximately the same in all nuclei

Less quenching than in single beta decay

Pastore, et al, 2017

Outlook

- More quantitative understanding of neutrinos and neutrino-nucleus interactions is being developed

- Good Description of data in light nuclei across a range of energy and momenta

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

- And to understand astrophysical environments and observations
    - R-process nucleosynthesis in supernovae / n-star mergers
    - Neutron star cooling
    - R-process nucleosynthesis and weak matrix elements