Neutrino-Nucleus Scattering
CANHP 2015

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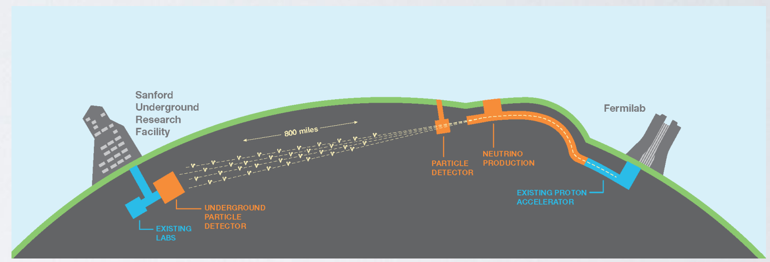
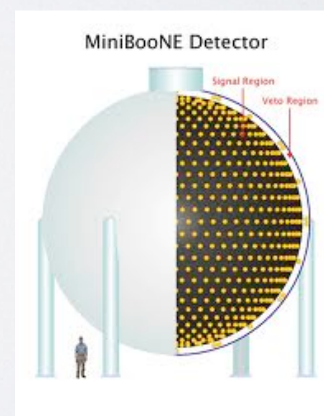
Inclusive Neutrino-Nucleus & Electron-Nucleus Scattering:

- Motivation
- Ingredients: Interactions and Currents
- Correlations
- Simplified Models of Response
- Sum Rules
- Euclidean Response and Inversion
- Future Directions





Combination of Understanding and Using Nuclei to Probe Neutrino Physics

Understanding Nuclei:

- Nuclear Interactions
- Neutron-Rich Nuclei
- Electroweak Processes

Using Nuclei to Probe Fundamental Physics:

- Neutrino Scattering
- Neutrinoless Double Beta Decay

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.

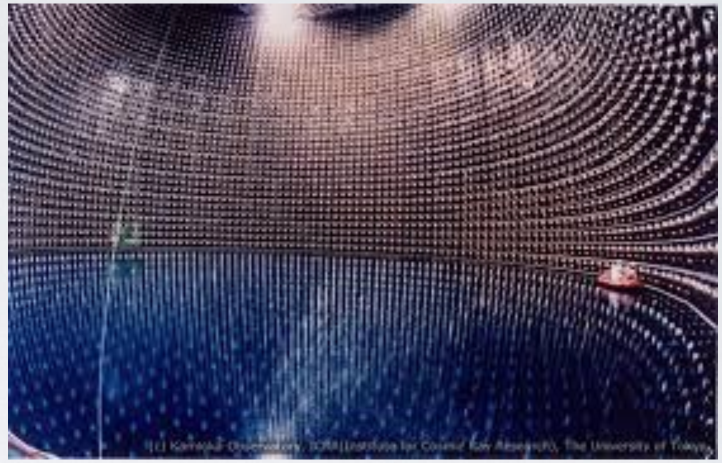
Reines was a LANL T-division employee at the time.

Reines and Cowan were awarded the Nobel Prize in 1995.

They discovered the electron (anti-) neutrino,
later Lederman, Schwartz and Steinberger detected
muon neutrino, receiving the 1998 Nobel Prize.

2015 Nobel Prize in Physics

Takaaki Kajita



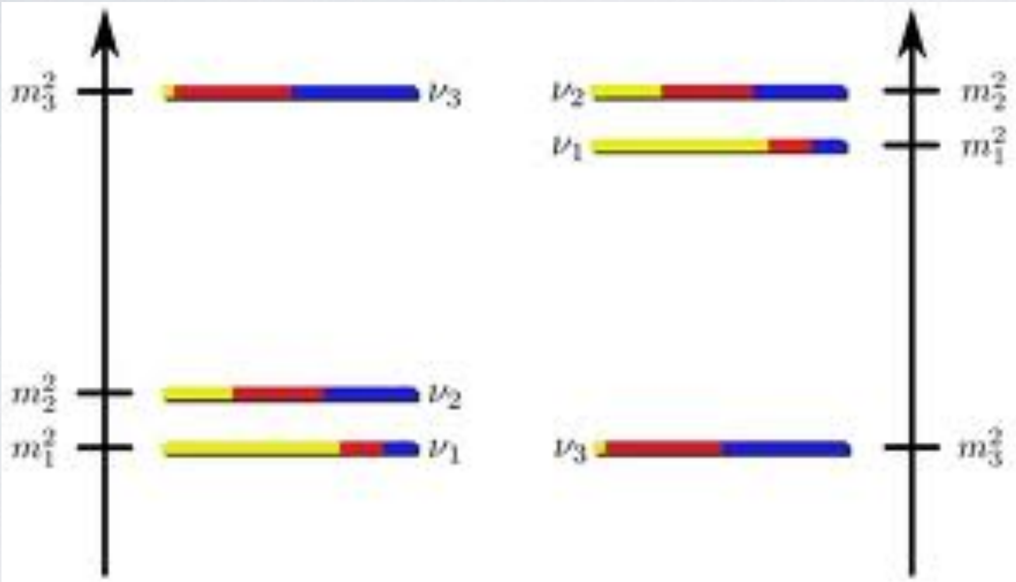
Super Kamiokande
Atmospheric Neutrinos

Neutrinos
Oscillate
Between Flavors
=
Neutrinos
have mass

Art McDonald

SNO
Solar Neutrinos

Neutrino Masses



normal inverted

measuring masses, mixings from neutrino oscillations

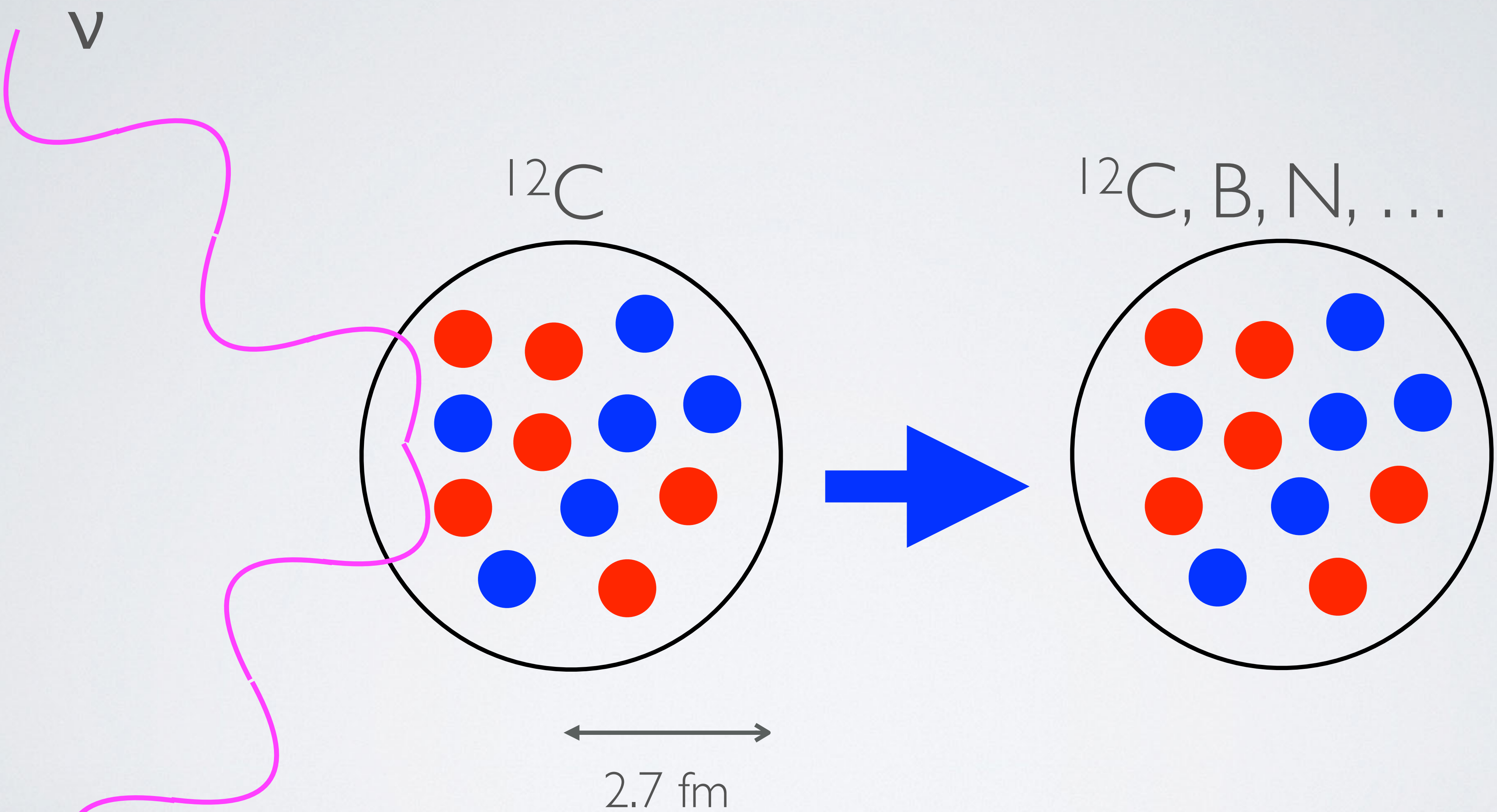
Mass Hierarchy, CP violation not yet known

Simplified two-flavor neutrino oscillations:

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\mathrm{GeV}}{\mathrm{eV}^2\,\mathrm{km}}\right).$$

Ratio of E/L to Δm^2 critical

Low-Energy Neutrinos and Nuclei

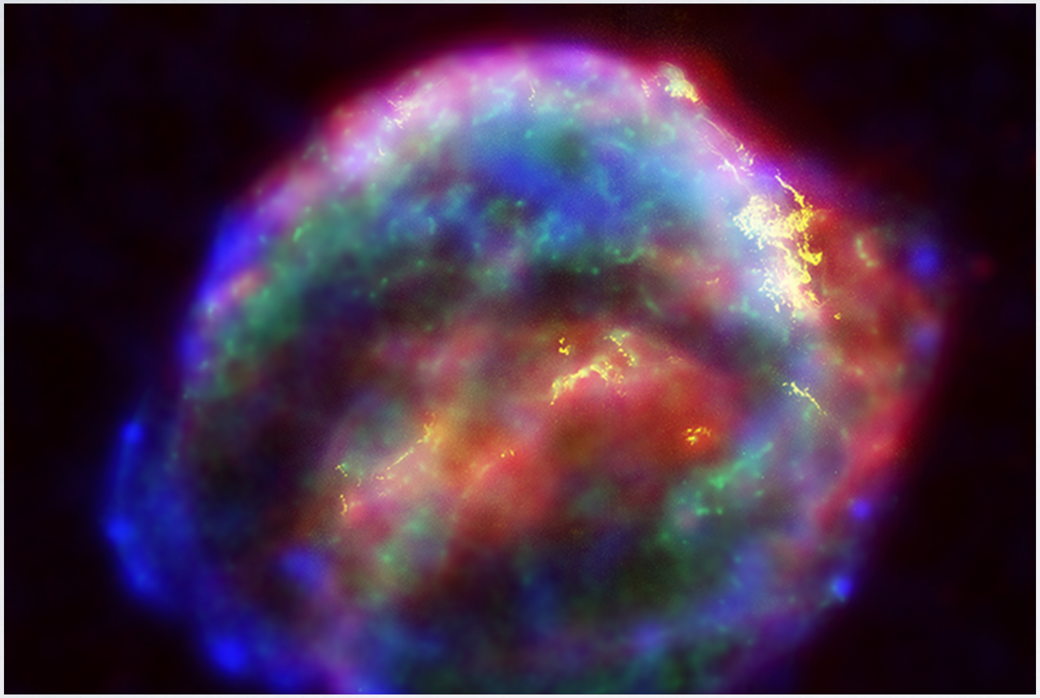


wavelength comparable to nuclear size

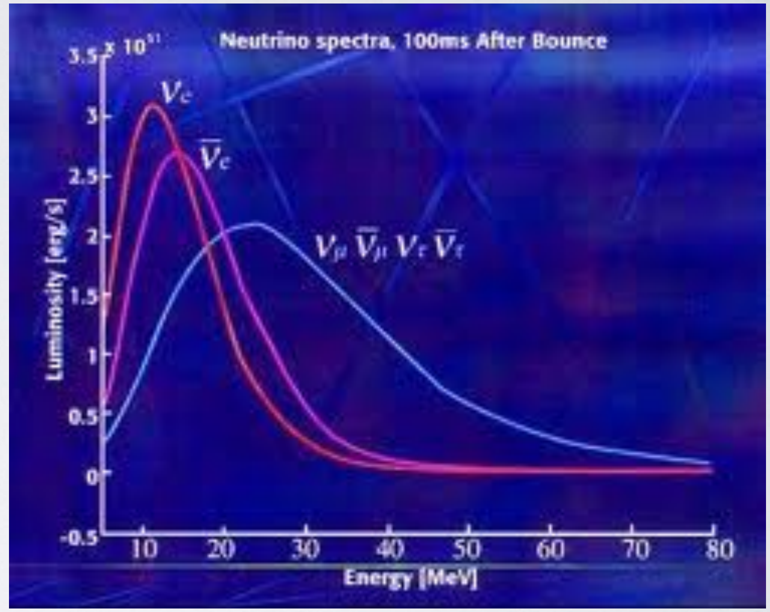
Typically to one or a few nuclear states

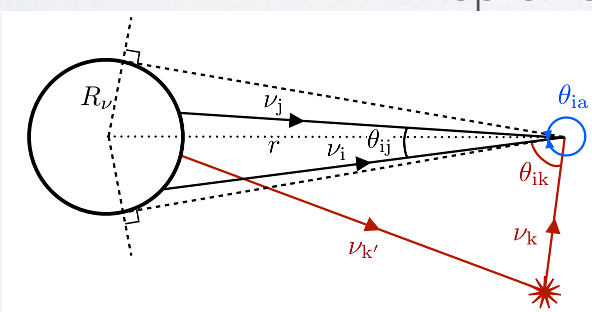
Supernovae and Astrophysical Neutrinos

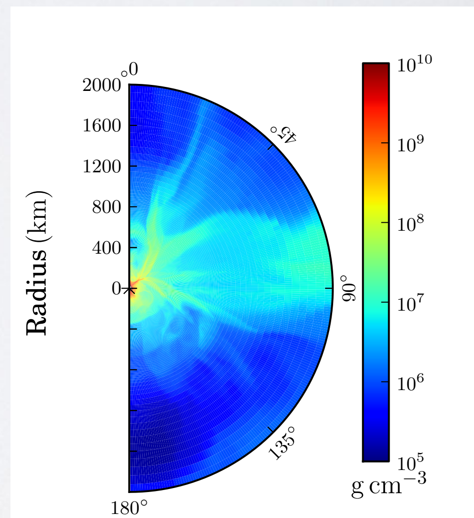
Different Sources, time dependence, different epochs



Kepler Supernova





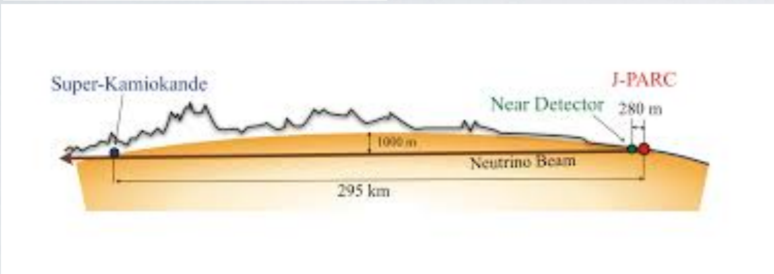


Coherent Oscillations, MSW in turbulent regime, ...

Can we make r-process nuclei in supernovae ?

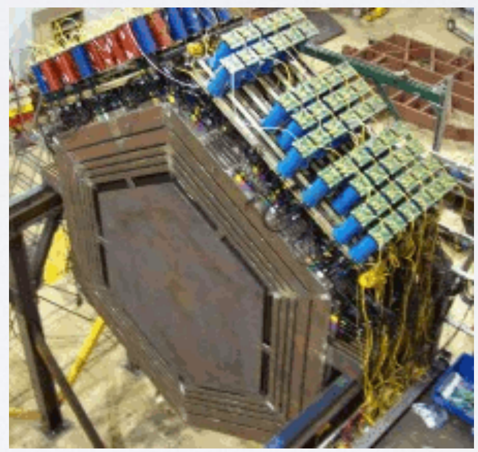
Accelerator Neutrinos

T2K

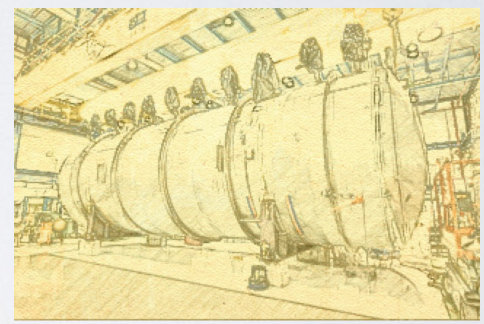


MINOS

SuperK



MINERva



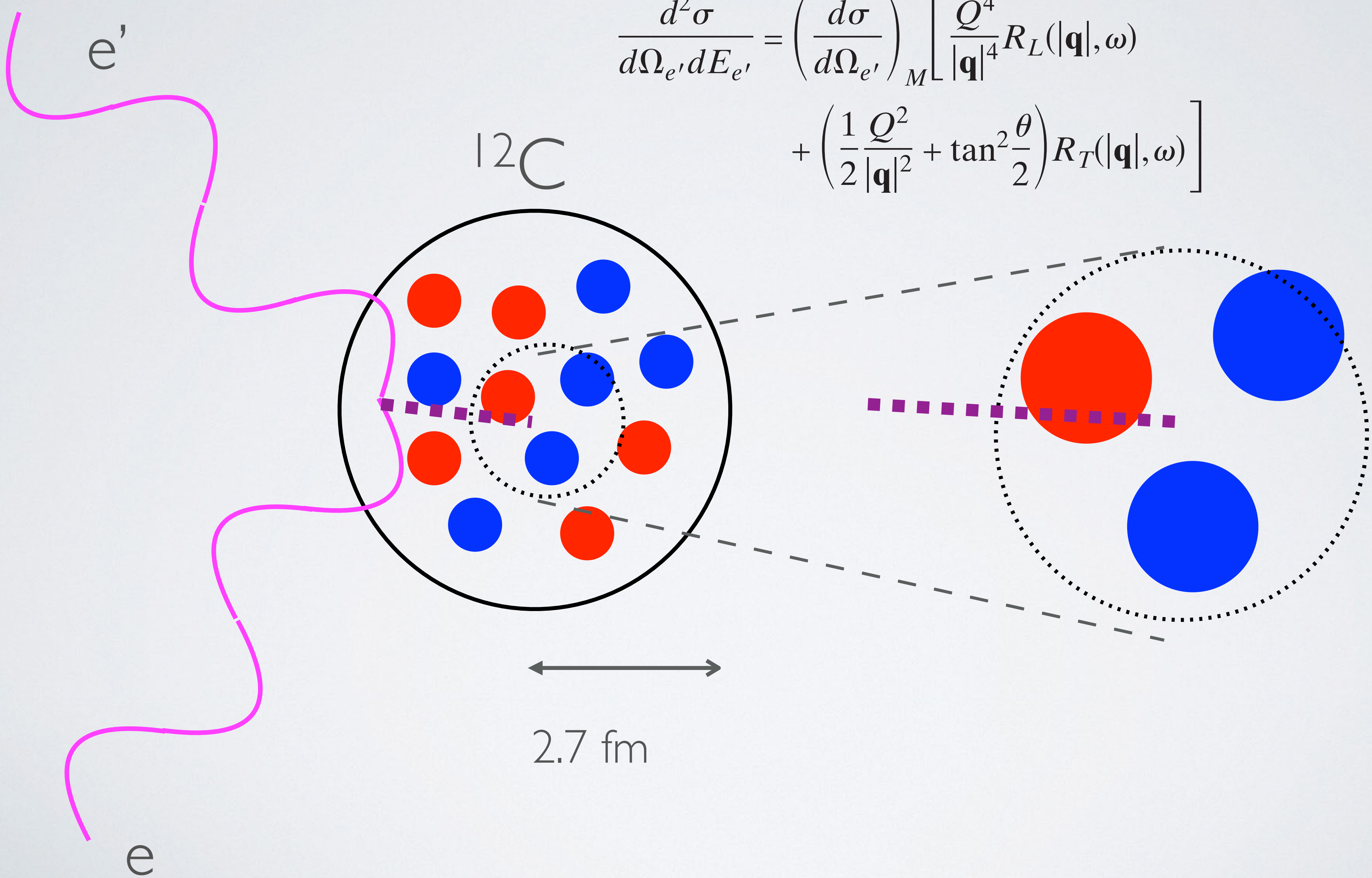
MicroBooNE

Advantages: Control over Energy, flux

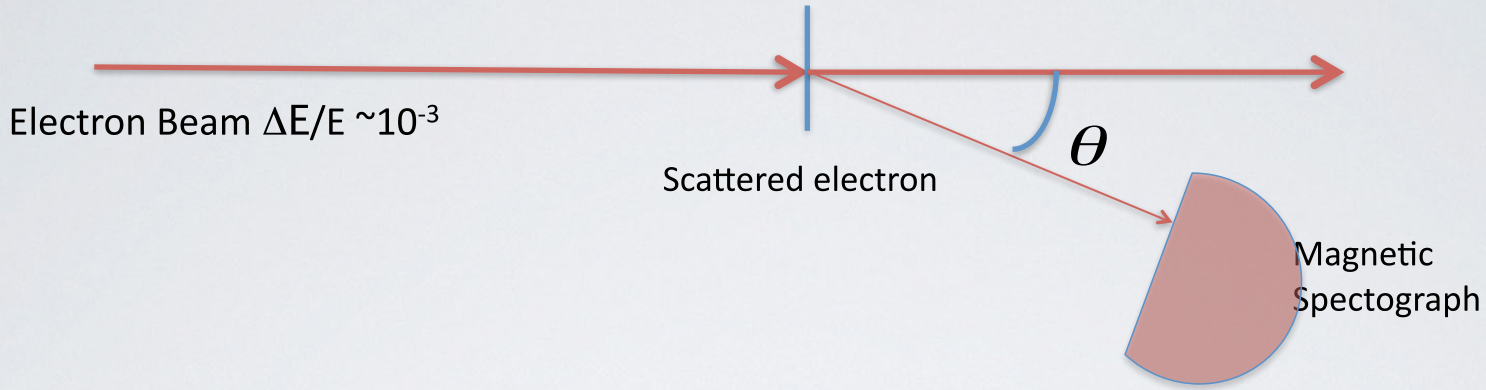
neutrino 'beams' can be sent over long distances

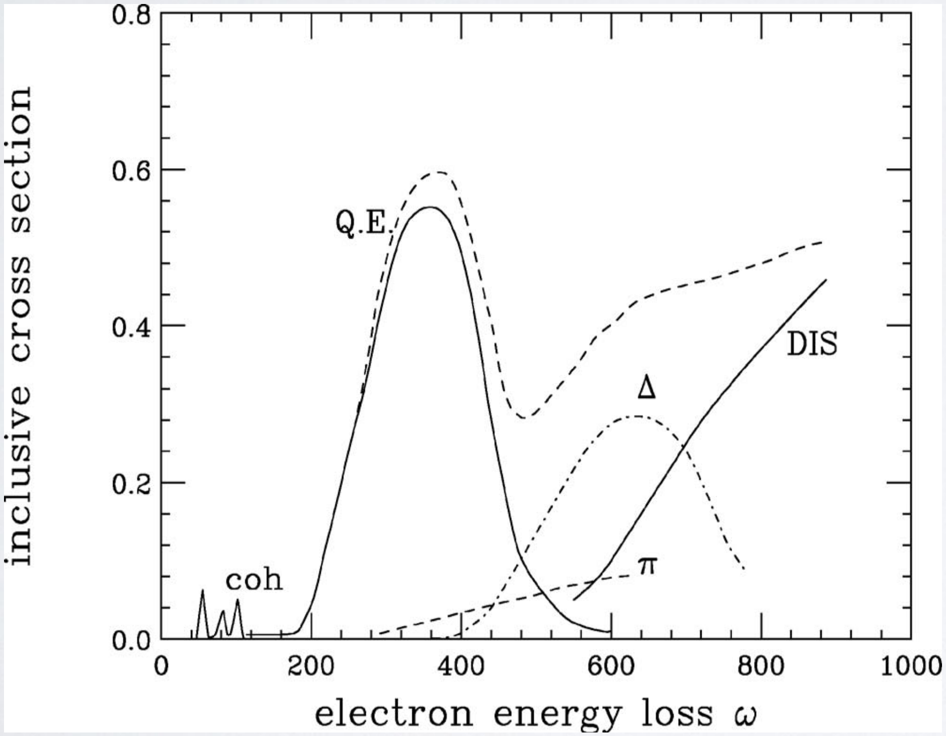
Inclusive electron scattering,
measure electron kinematics only

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



Inclusive Electron Scattering





$$(E,0,0,p),\ \ (E',p'\sin\theta,0,p'\cos\theta)$$

$$\omega \equiv E - E'$$

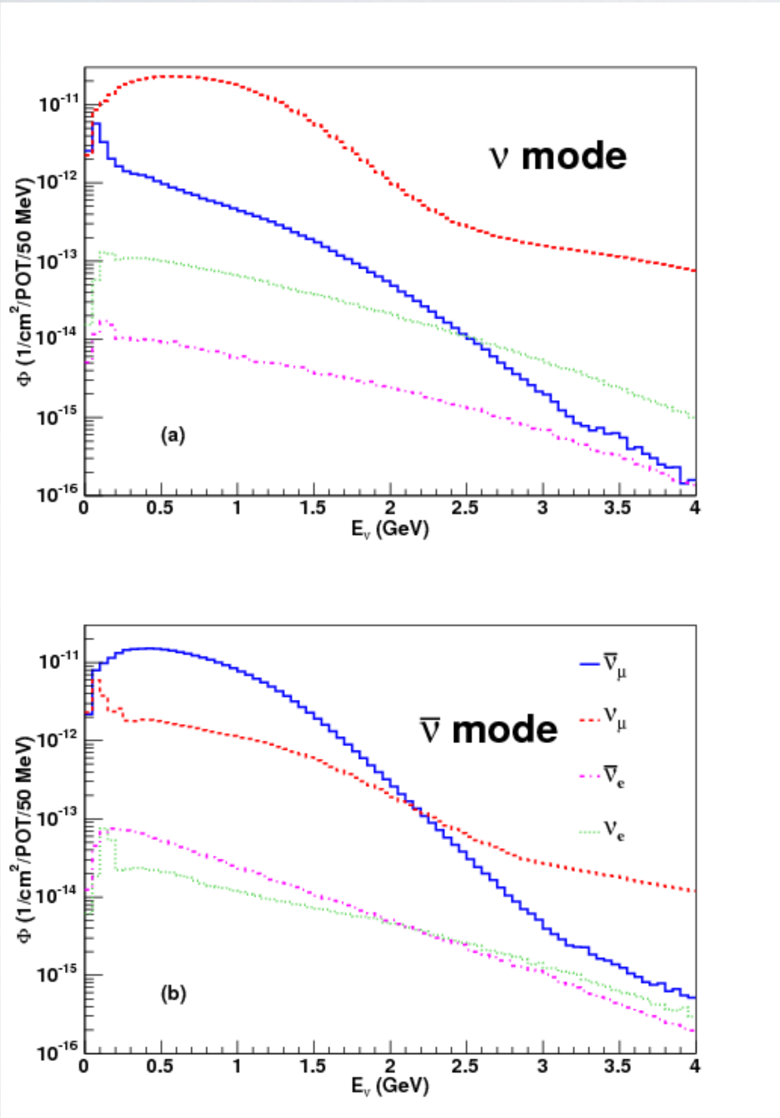
$$\vec{q} = \vec{p} - \vec{p}\,'$$

Thus q and ω are precisely known <u>without any reference to the nuclear final state</u>

from Benhar, Day, Sick, RMP 2008

Neutrino Scattering: Beam Flux

MiniBoone Flux Estimates



Incoming beam very broad
Measure outgoing lepton's energy and angle

Infer initial **ν** or anti-**ν** energy
Require L/E to get oscillation parameters

Why are 'local' properties enough?
Simple view of Nuclei: inclusive scattering

Charge distributions of different Nuclei:

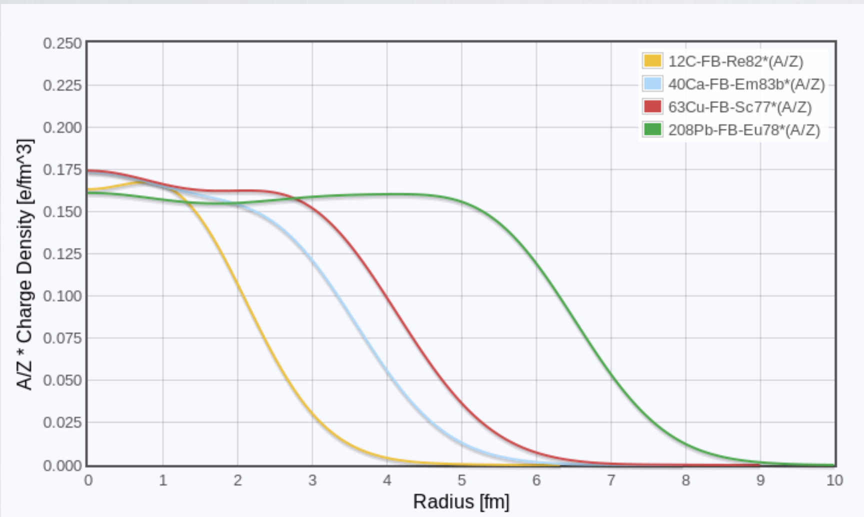
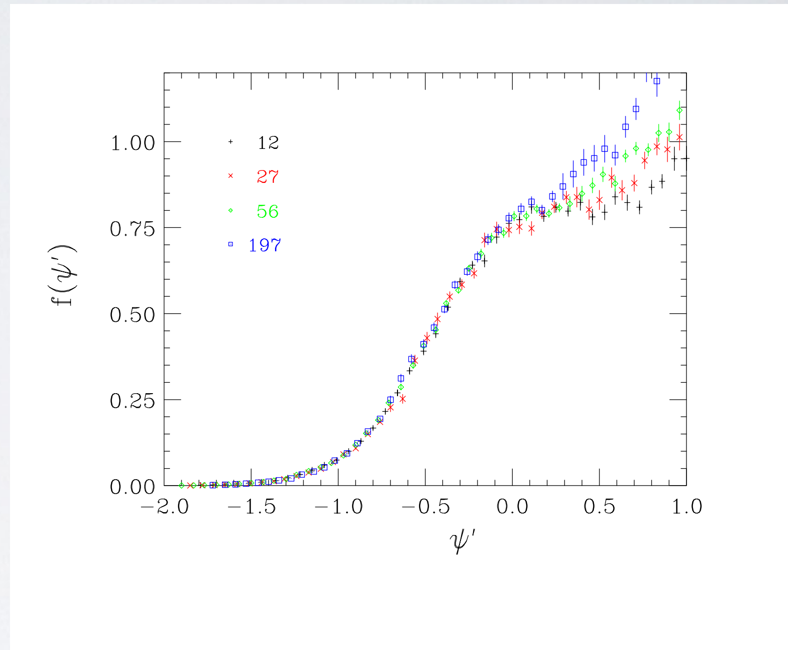


figure from faculty.virginia.edu/ncd
based on work of Hofstadter, et al.: Nobel Prize 1961

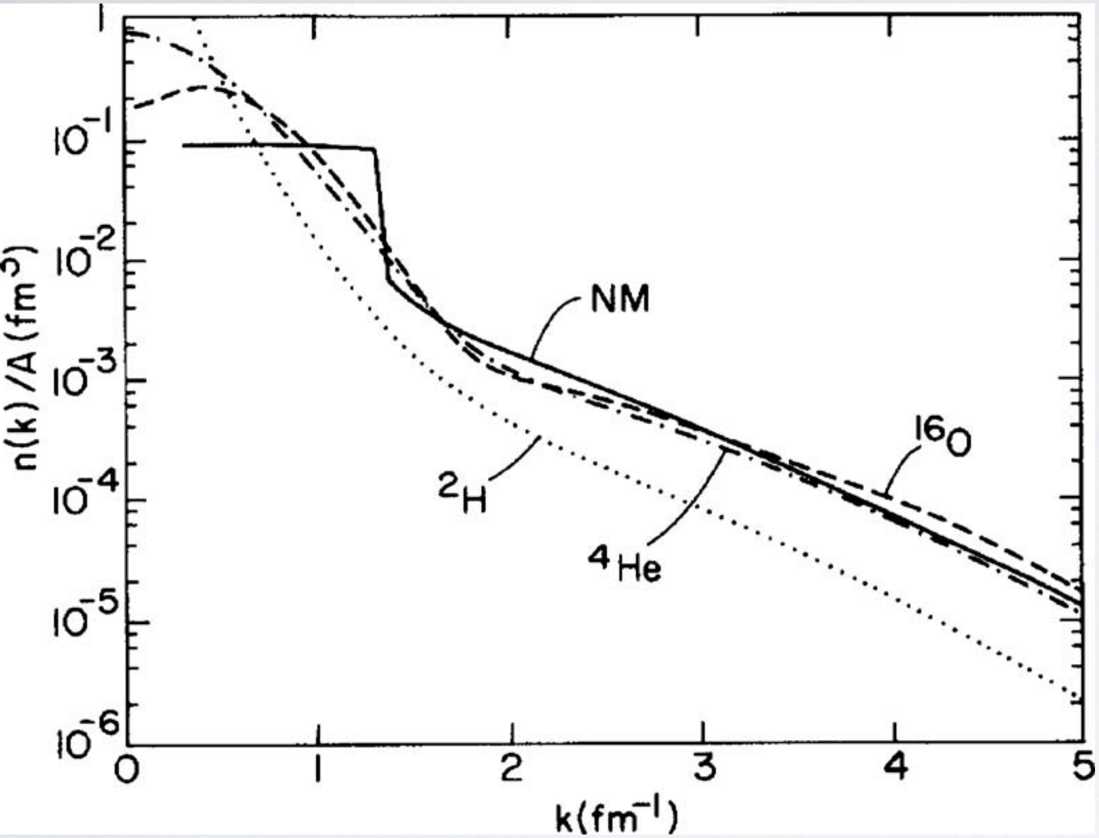
Scaling (2nd kind) different nuclei



Donnelly and Sick, 1999

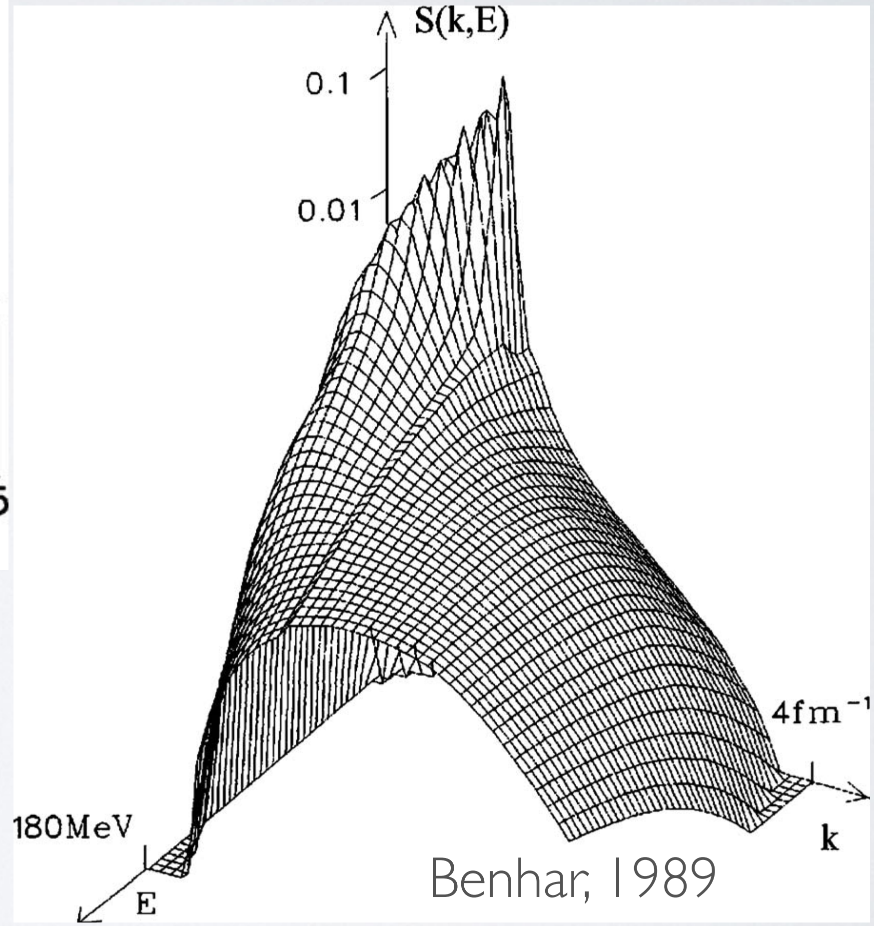
Inclusive scattering measures properties at distances $\sim \pi / q \lesssim 1$ fm

Momentum Distributions and Spectral Functions



Schiavilla, et al 1986, Benhar, et al 1993

Spectral Function in NM



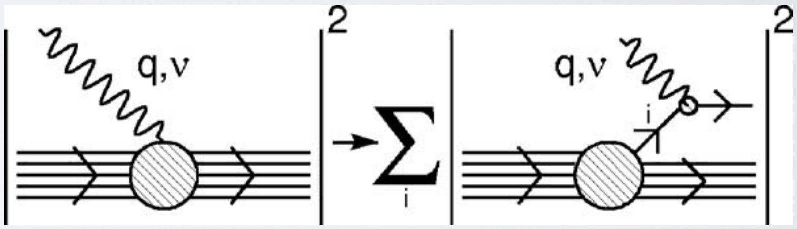
Benhar, 1989

Response in PWIA

$$R\ (q,\omega)\ =\ \sum_i \langle\ 0\ |\rho_i^\dagger(q;r')\ \rho_i(q;r)|0\rangle\ \delta(E_F - E_I - \omega)$$

Requires one-body off-diagonal density matrix:
momentum distribution

$E_F = q^2/(2m) + \Delta$ including a mean-field shift



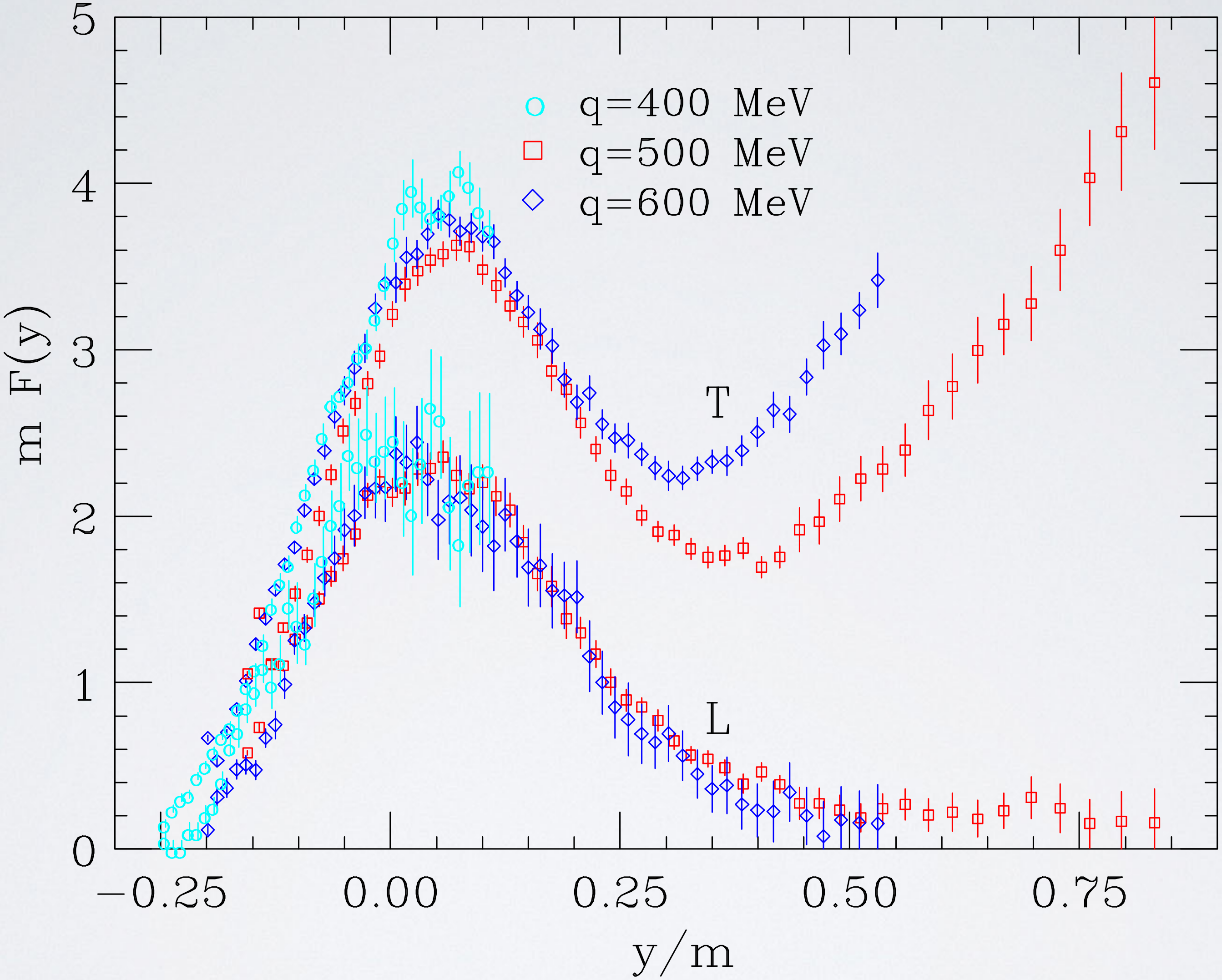
Spectral function:

includes energy of A-1 particles not interacting with the probe

$$R\ (q,\omega)\ =\ \sum_i \sum_f \langle 0\ |a_i^\dagger(q;r')|f_{A-1}\rangle\ \langle f_{A-1}|\ a_i(q;r)|0\rangle\ \delta(E_F - E_I - \omega)$$

$E_F = q^2/(2m) + \Delta + E_{f,A-1}$

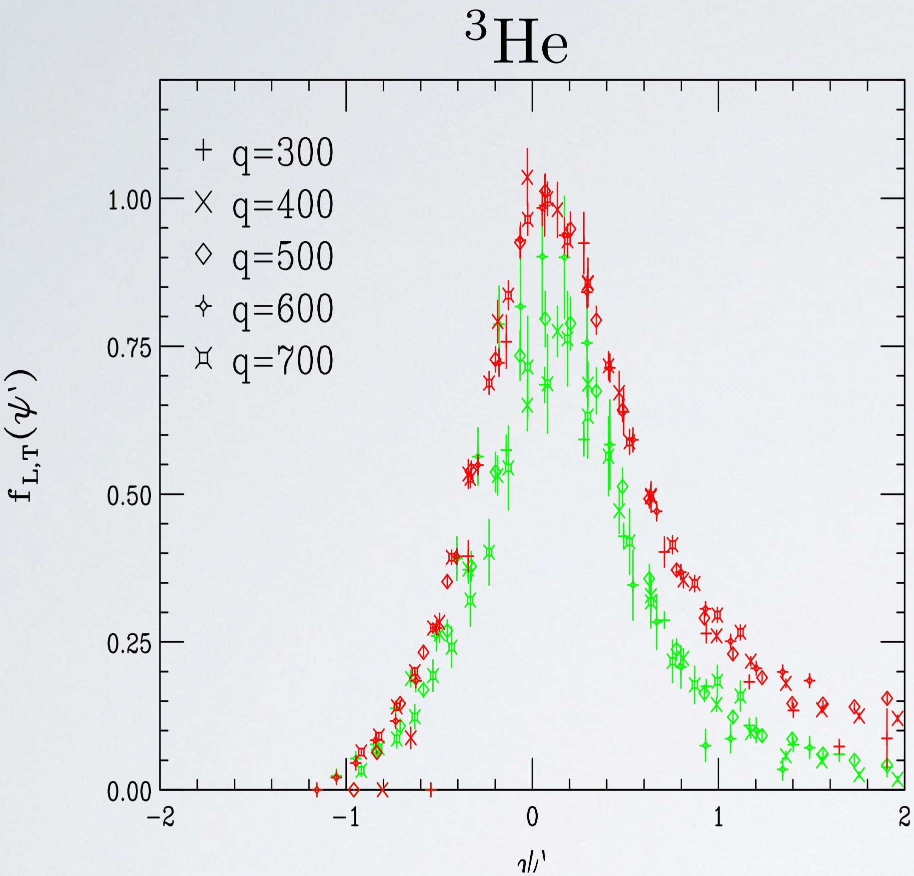
Longitudinal/Transverse separation in electron scattering: ^{12}C

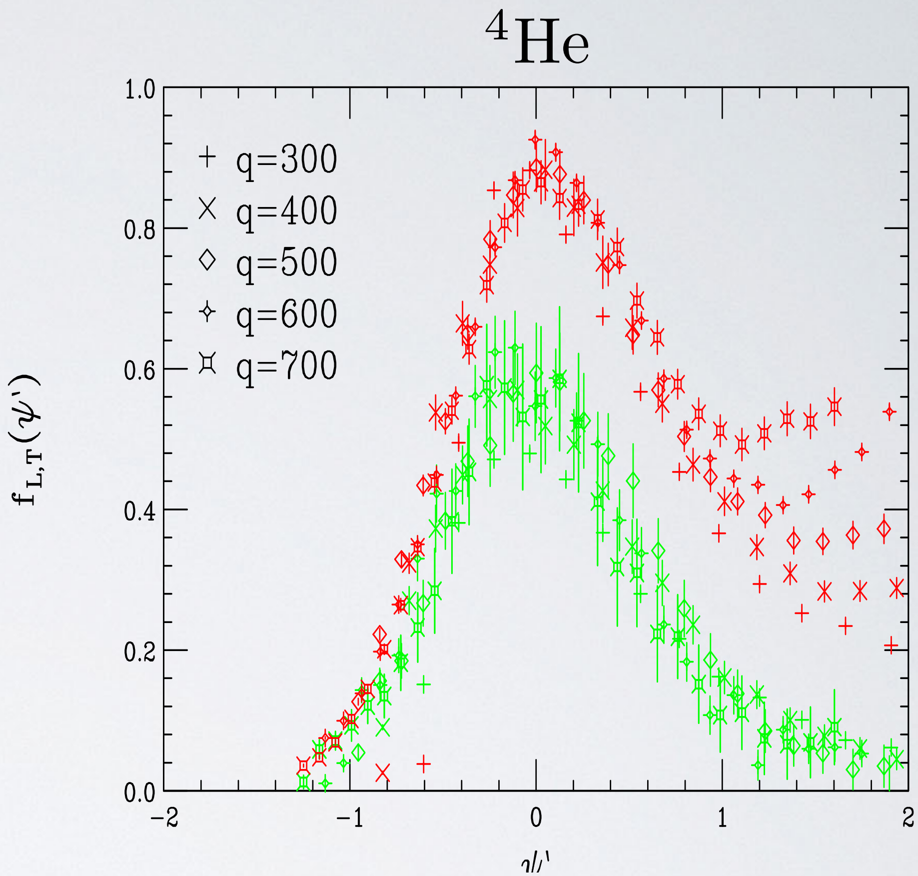


from Benhar, Day, Sick, RMP 2008
Benhar, arXiv: 1501.06448
data Finn, et al 1984

(e, e') Inclusive Response: Scaling Analysis

Donnelly and Sick (1999)





Single nucleon couplings factored out
Momenta of order inverse internucleon spacing:
Large enhancement of transverse over longitudinal response

in all nuclei

Inclusive Scattering

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

electron scattering

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

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

Full Response: Ground State (Hamiltonian)
Currents
Final states

What we can compute reliably?
(given the interaction/ current model)

$$R_{L,T}\ (q,\omega)\ = \sum_f\ \delta(\omega\ +\ E_0\ + E_f)\ |\ \langle\ f\ |\mathcal{O}_{\mathcal{L},\mathcal{T}}\ |\ 0\ \rangle\ |^2$$

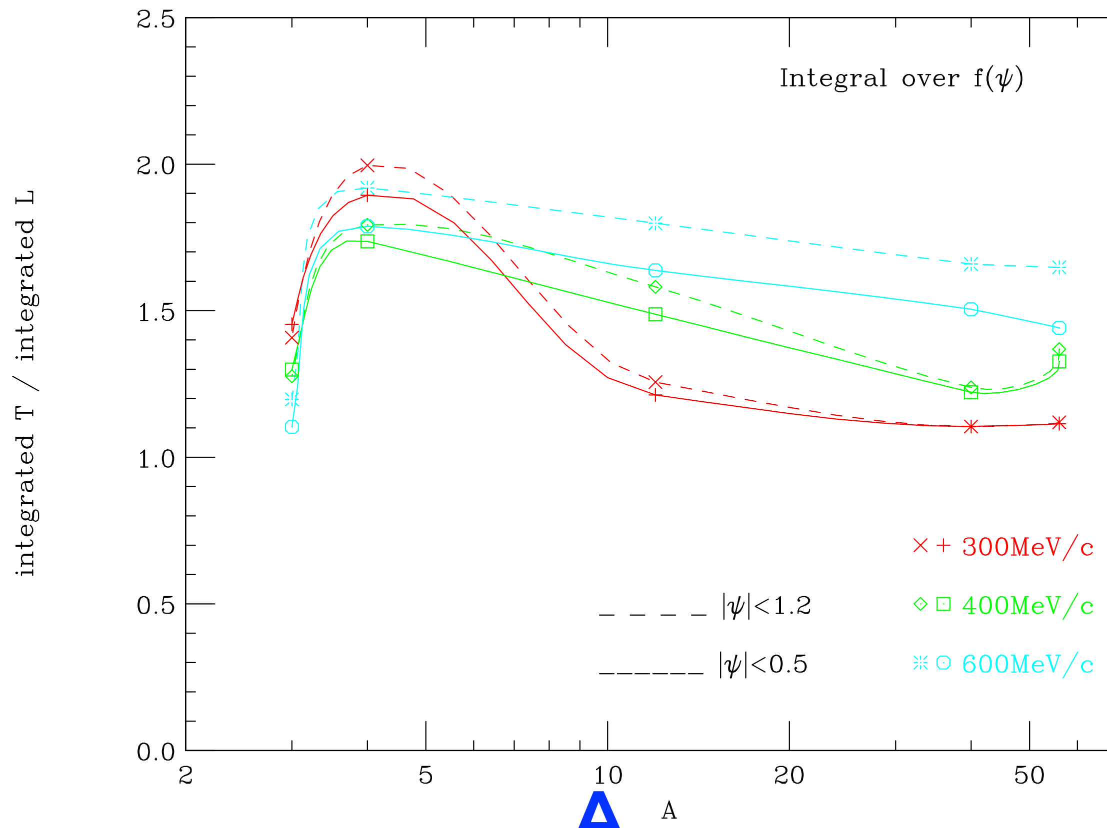
Sum Rules: `easy' to calculate
ground-state observable

$$S(q)\ =\ \int d\omega\ R(q,\omega) = \langle 0|O^\dagger(q)\ O(q)|0\rangle$$

Tells us about ground-state structure:
enhancements/depletions tells us about
currents and correlations

Experimental Data on Sum Rules

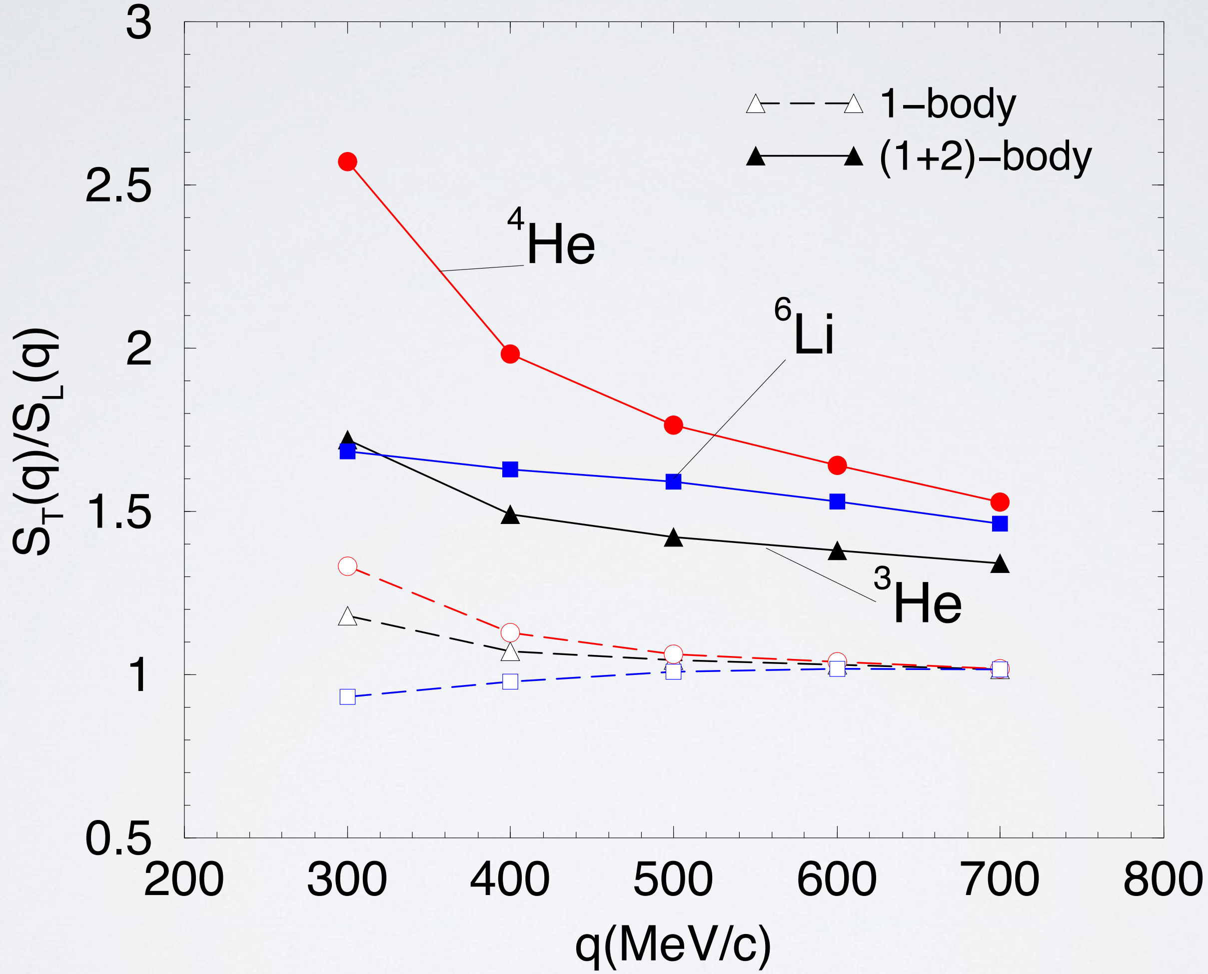
Transverse / Longitudinal Sum



A

Carlson, et al, PRC, 2002

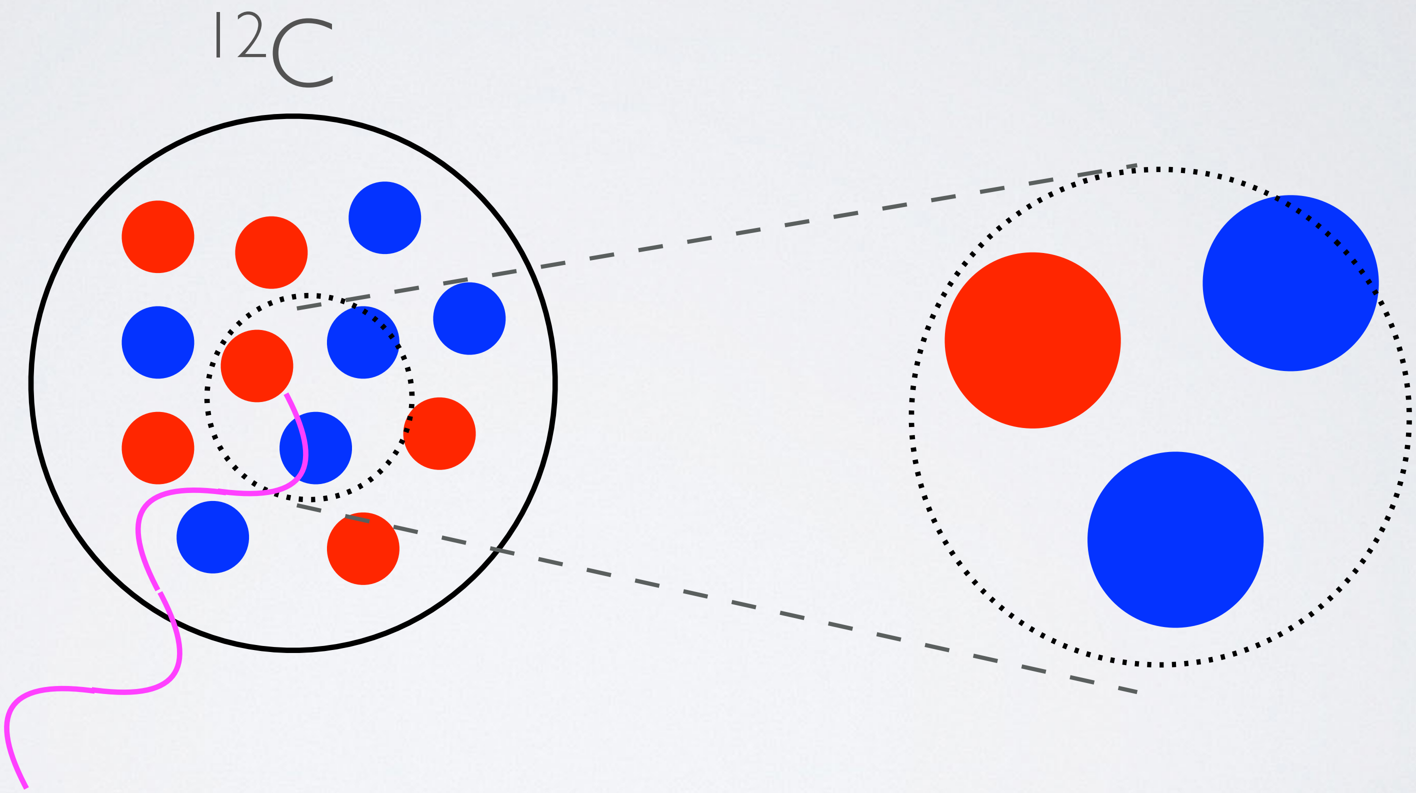
Transverse to Longitudinal Sum Rules for Light Nuclei



Carlson, Jourdan, Schiavilla, Sick, PRC, 2002

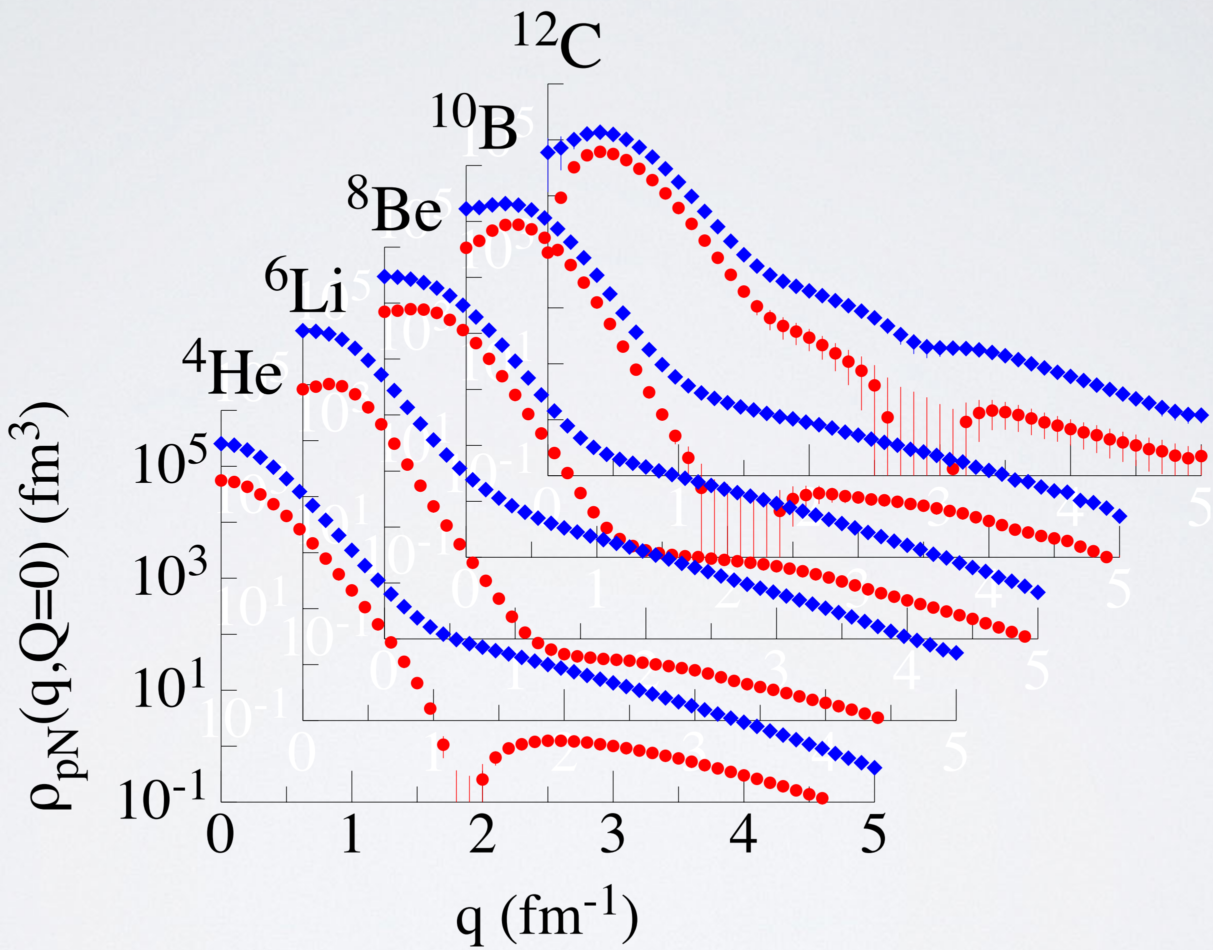
Contributions to Sum Rules

Ground State (low-momentum piece):
external momentum is large (≧ Fermi momentum)



For a large momentum transfer to have an important matrix element,
need contribution from pion-exchange interaction (correlations) or currents

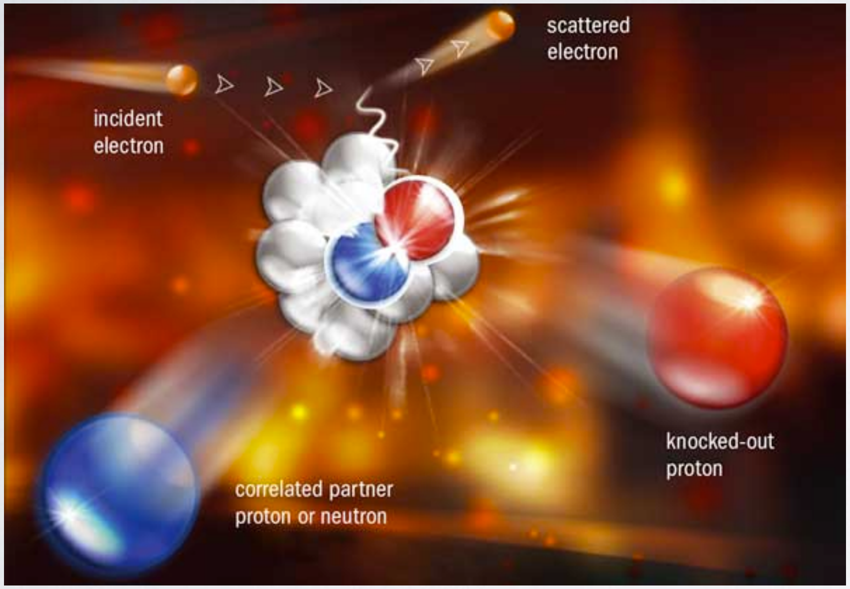
Correlations and Sum Rules: Two-Nucleon Momentum Distributions

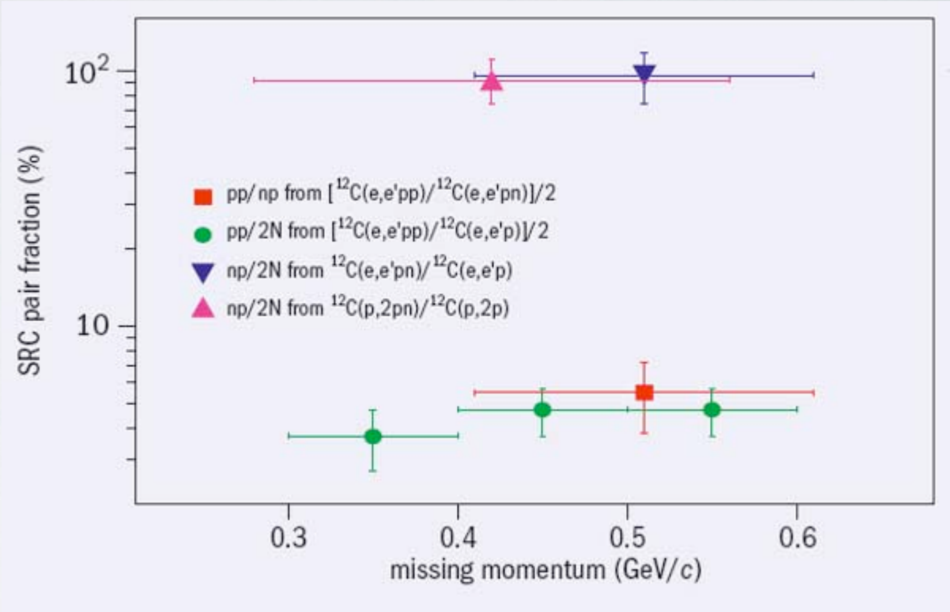


np vs. pp momentum distributions

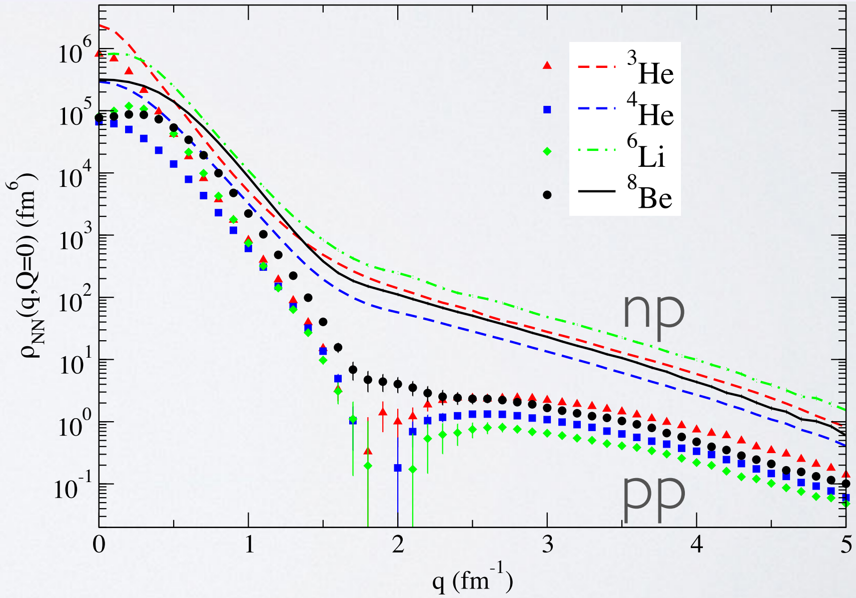
Carlson, et al, arXiv:1412.3081

JLAB, BNL back-to-back pairs in 12C
np pairs dominate over nn and pp



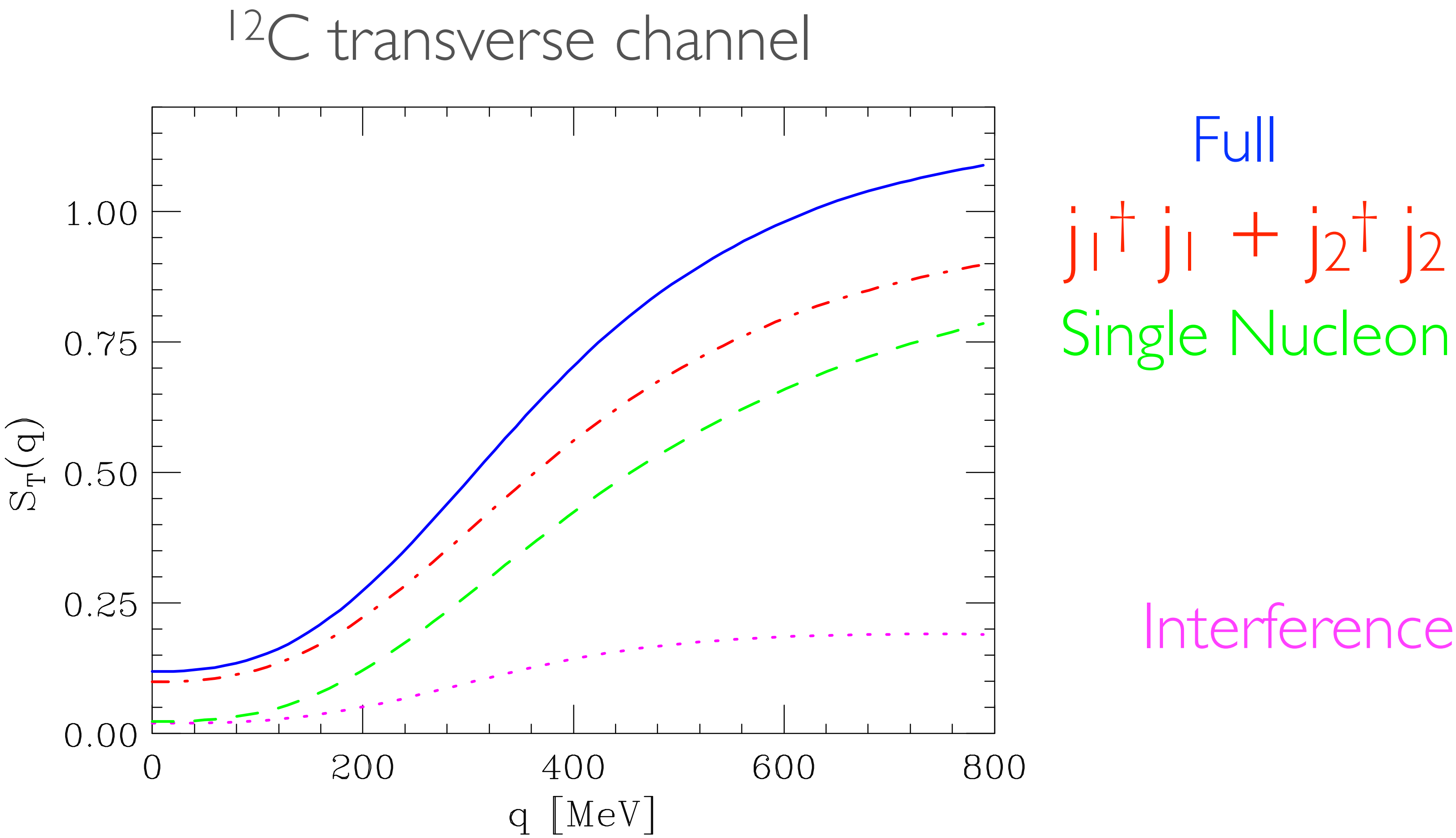


E Piasetzky *et al.* 2006 **Phys. Rev. Lett. 97** 162504.
M Sargsian *et al.* 2005 **Phys. Rev. C 71** 044615.
R Schiavilla *et al.* 2007 **Phys. Rev. Lett. 98** 132501.
R Subedi *et al.* 2008 **Science 320** 1475.



P=0 pair momentum distributions

Contributions to Sum Rules



Lovato and Benhar, 2013

Full Response function - Energy Dependence

$$R_{L,T}\ (q,\omega)\ = \sum_f\ \delta(\omega\ +\ E_0\ + E_f)\ |\ \langle\ f\ |\mathcal{O}_{\mathcal{L},\mathcal{T}}\ |\ 0\ \rangle\ |^2$$

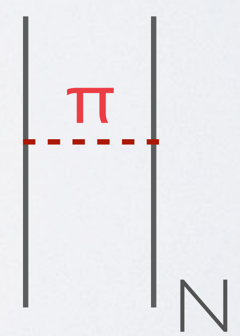
Imaginary Time (Euclidean Response)
correlation functions: statistical mechanics
no assumptions about which final states involved

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

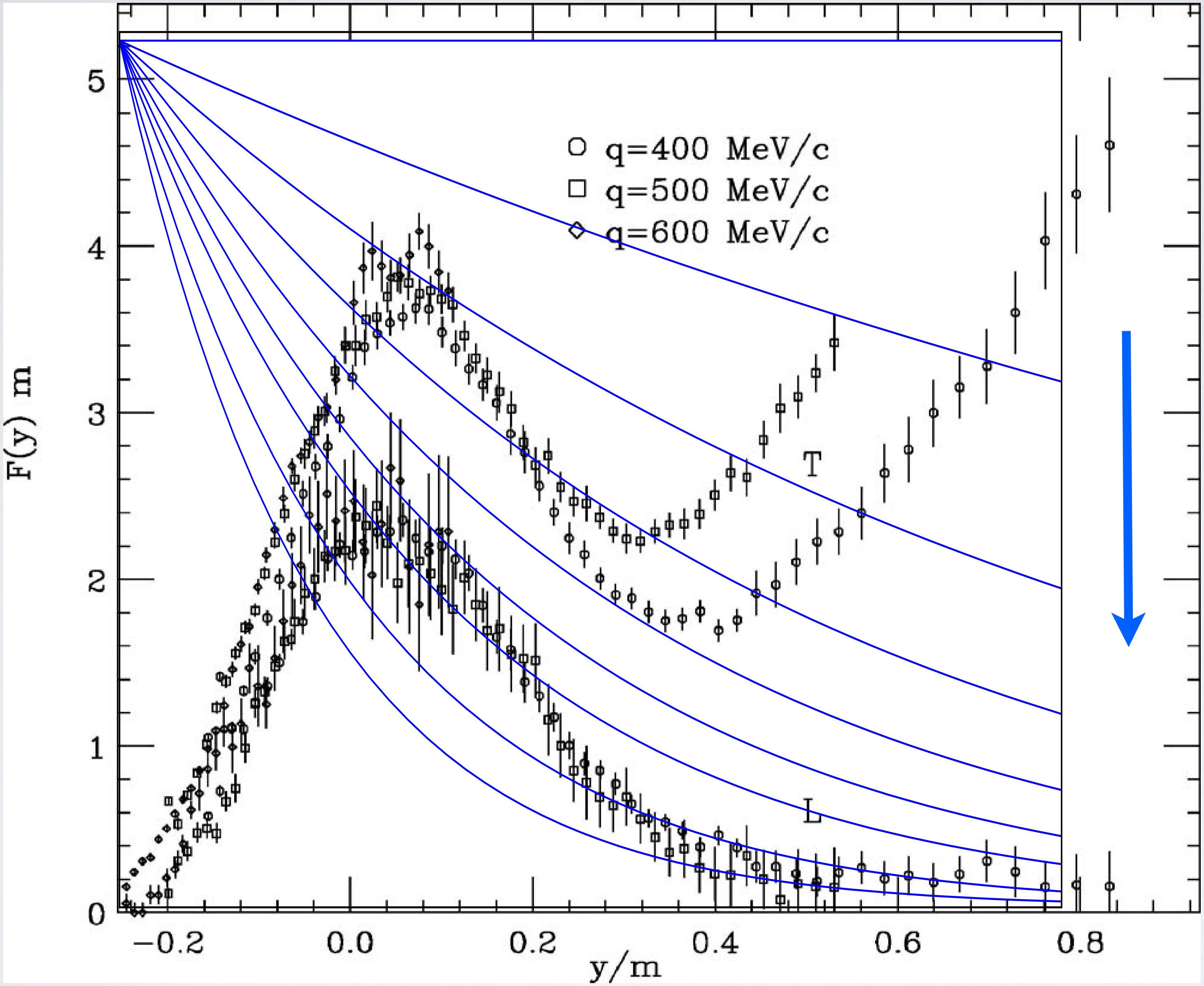
Tells us about energy dependence of the response

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

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



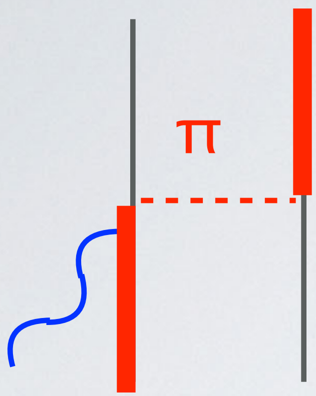
Euclidean Response



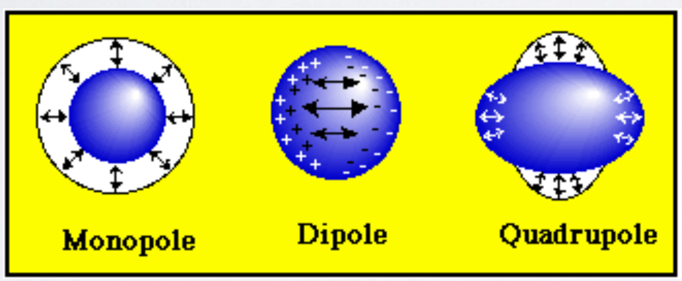
τ = inverse T

Sum rule → elastic FF^2 w/ increasing τ

Beyond Momentum Distributions



Charge propagation
via pion exchange
light mass - enhanced high energy response



from Ganil

Multiple nucleons,
giant resonances
low energy modes

These processes broaden and shift response from simple models

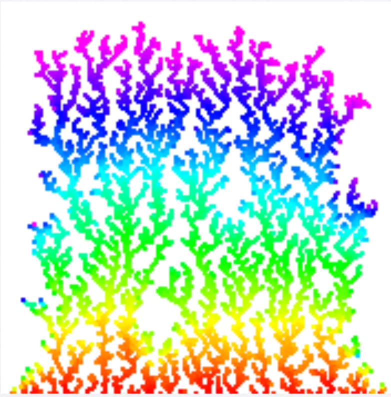
Euclidean Response

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

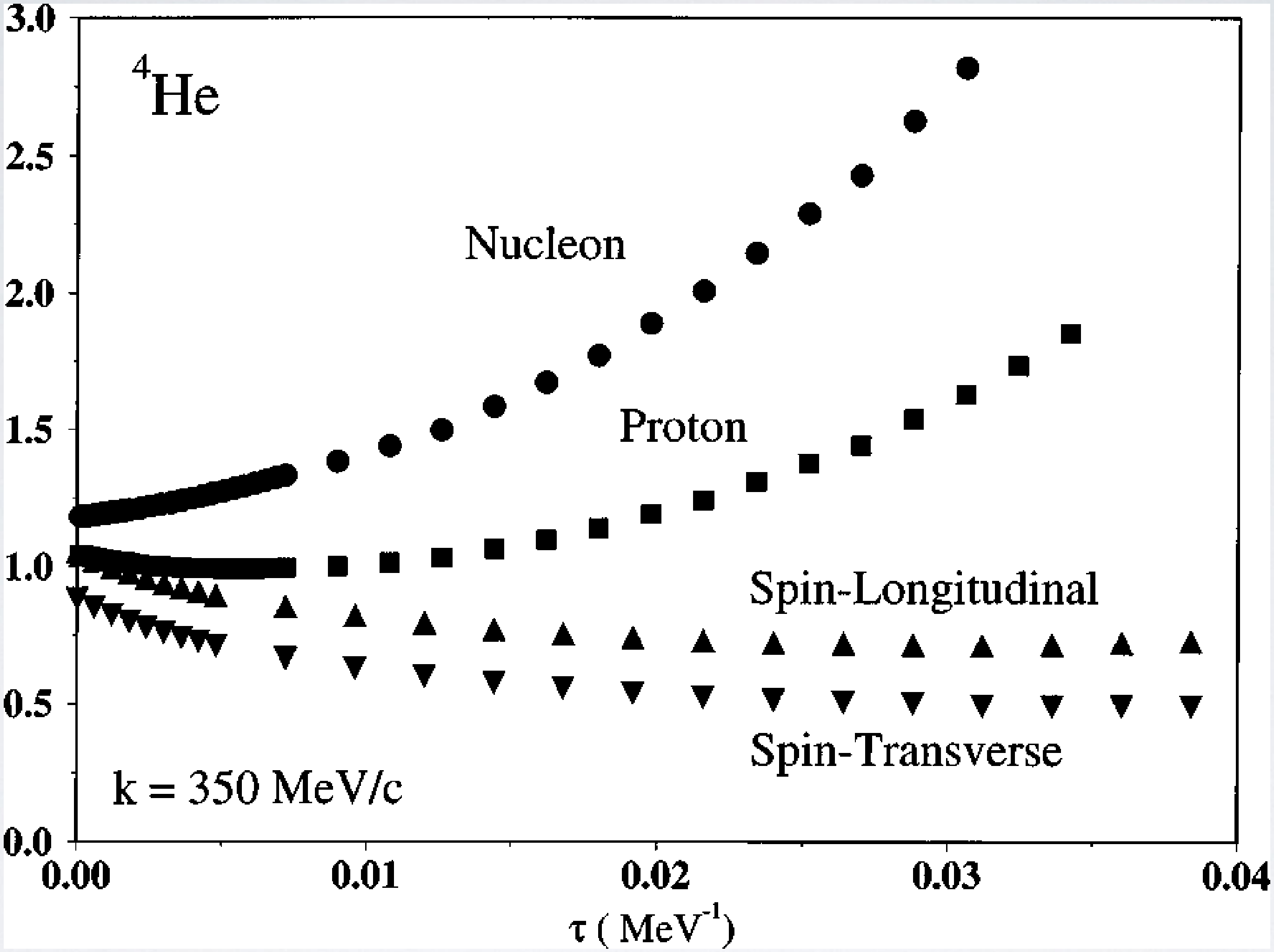
short `time' τ - high energy

- Exact given a model of interactions, currents
- Full final-state interactions
- `Local' Operator
- Can apply to any nucleus; no assumptions about final states
- All contributions - elastic, low-lying states, quasi elastic, … are included

$$\exp[-H\tau] \; \approx \; \exp[-V\tau/2]\exp[-T\tau]\exp[-V\tau/2]$$



Operator Dependence is Very Important



q = 350 MeV/c

Carlson and Schiavilla, RMP 1998

Neutrino Scattering: 5 response functions

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\epsilon'\mathrm{d}\Omega}\right)_{\nu/\overline{\nu}} = \frac{G_F^2}{2\pi^2}\,k'\epsilon'\cos^2\frac{\theta}{2}\left[R_{00} + \frac{\omega^2}{q^2}\,R_{zz} - \frac{\omega}{q}R_{0z}\right.$$

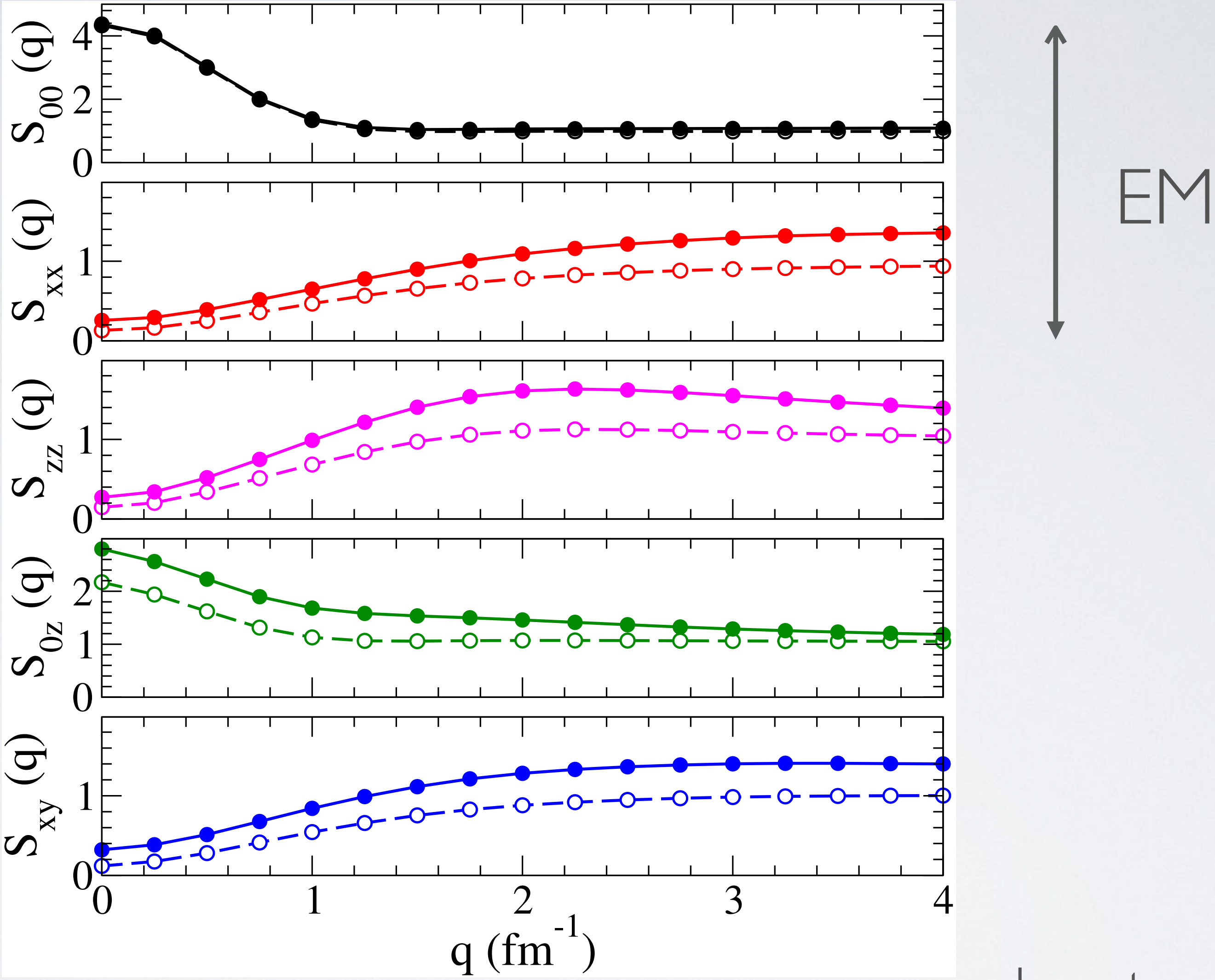
$$\left. + \left(\tan^2\frac{\theta}{2} + \frac{Q^2}{2\,q^2}\right)R_{xx} \mp \tan\frac{\theta}{2}\sqrt{\tan^2\frac{\theta}{2} + \frac{Q^2}{q^2}}\,R_{xy}\right] \,,$$

$$R_{\alpha\beta}(q,\omega) \sim \overline{\sum_i}\sum_f \delta(\omega + m_A - E_f)\langle f\,|\,j^\alpha(\mathbf{q},\omega)\,|i\rangle$$

$$\times\langle f\,|\,j^\beta(\mathbf{q},\omega)\,|i\rangle^* \;,$$

Vector - Axial Vector Interference determines the difference between neutrino and antineutrino scattering

Sum rules in 12C

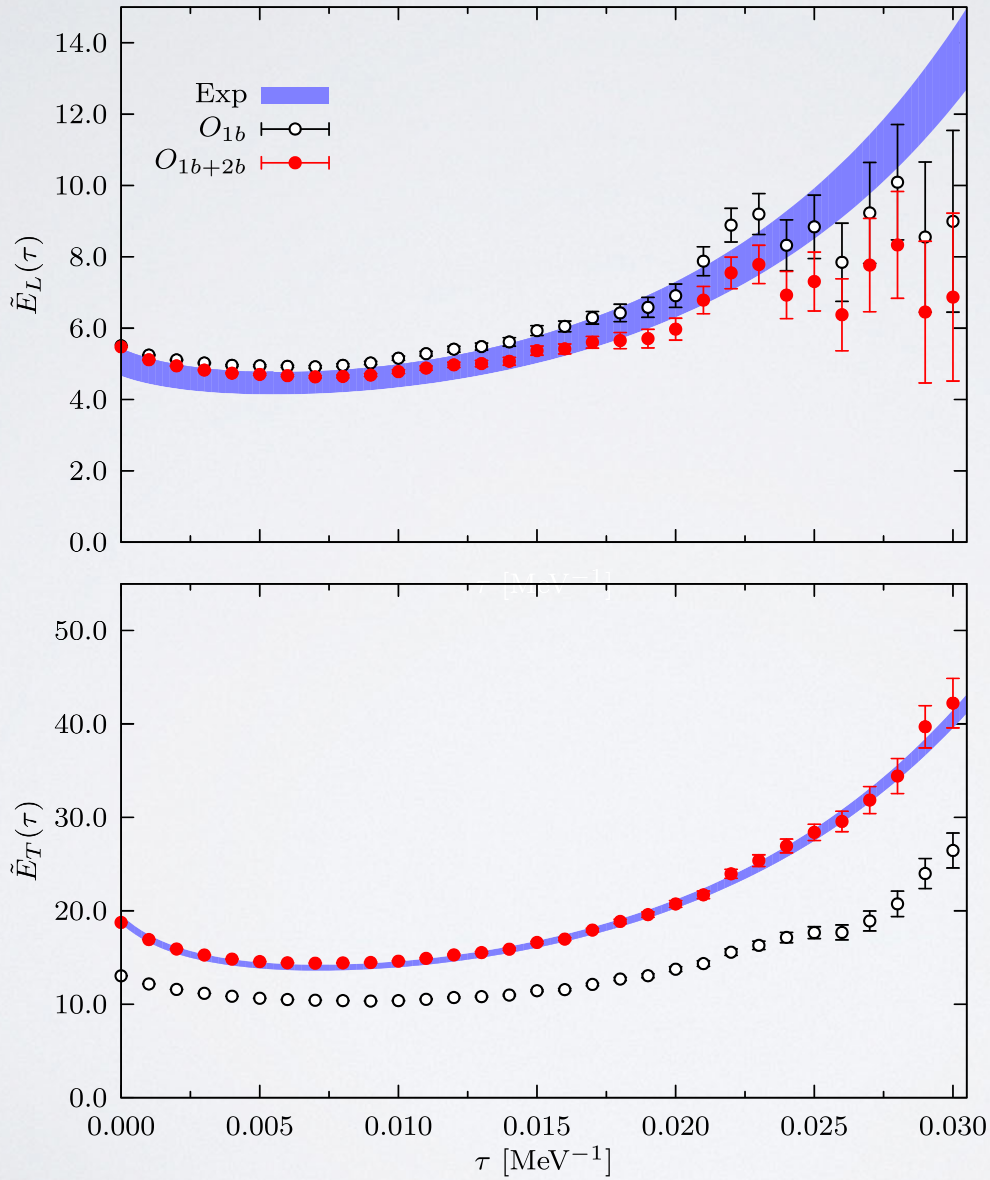


Lovato, et. al PRL 2014

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

^{12}C Euclidean Response: Electron Scattering

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



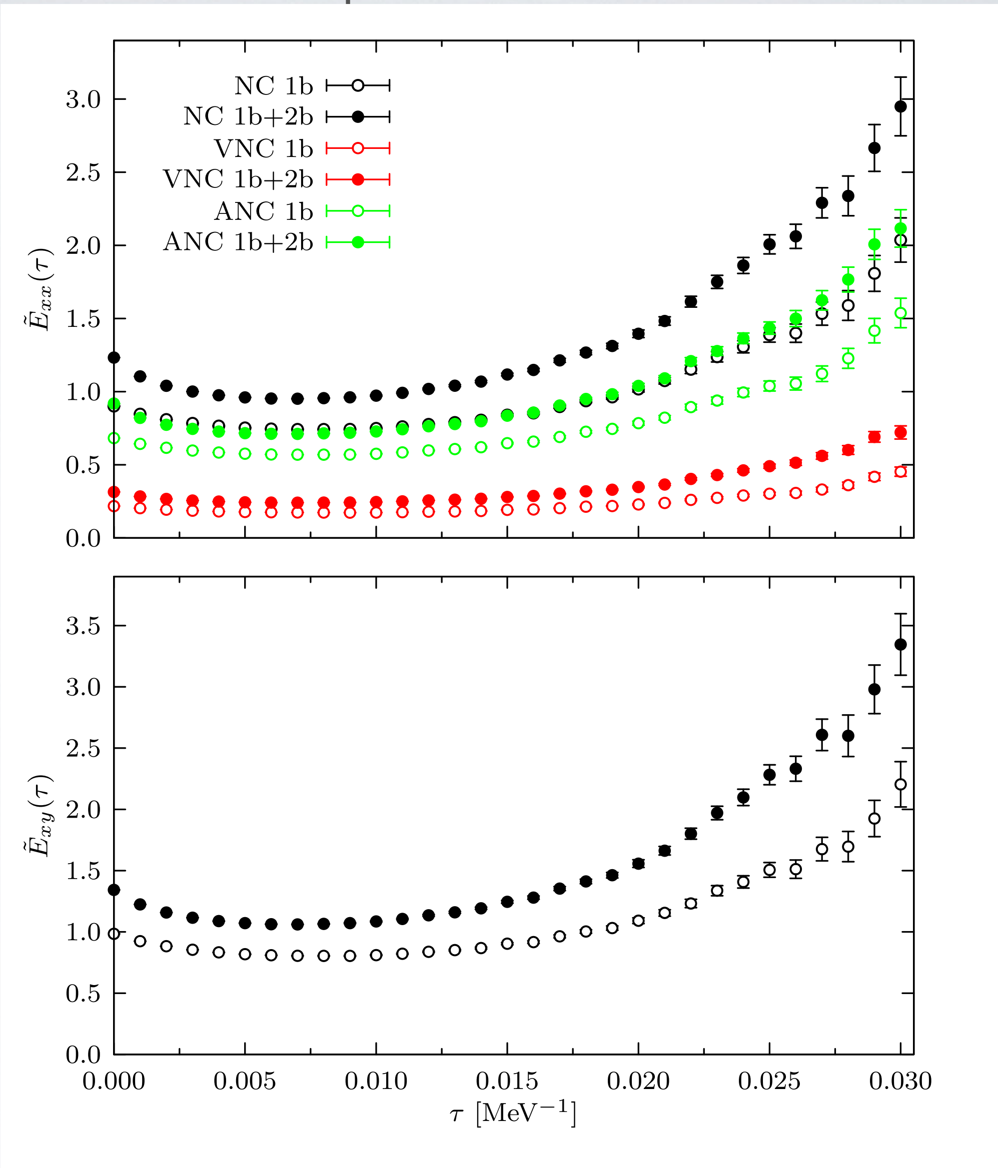
\`Local' Operator for E ≳ 100 MeV

Longitudinal

Transverse

Lovato, et al, arXiv:1501.01981. PRC 2015

^{12}C Euclidean Response: Neutral Current



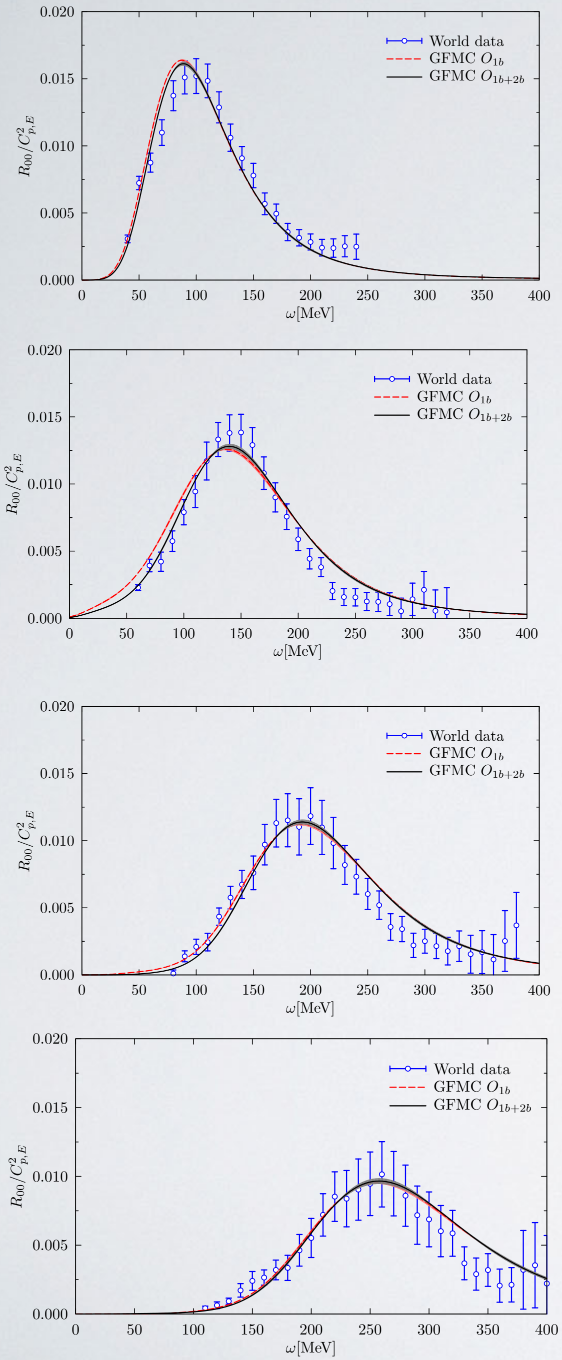
Lovato, et al, arXiv:1491,2605; 1501.01981

Enhancement of Axial current and V-A interference affects neutrino vs. anti-neutrino scattering: hierarchy and CP

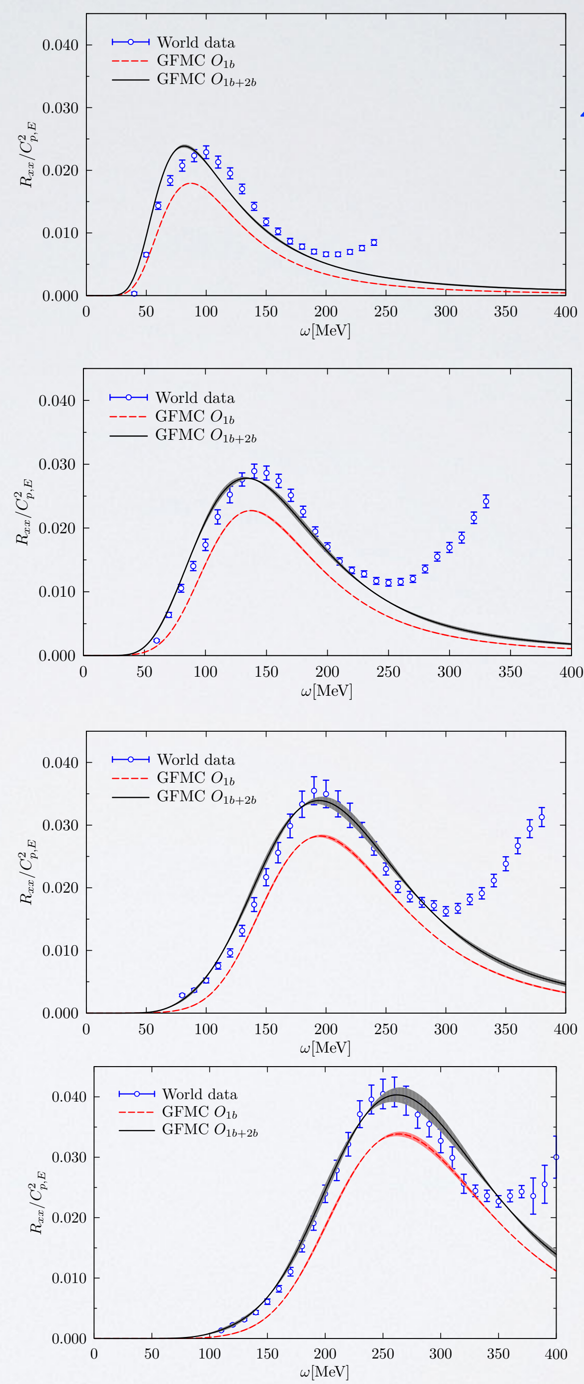
see Omar Benhar, Patrick Huber, Camillo Mariani, Davide Meloni: arXiv:1501.06448 for impact on oscillation parameters

^{4}He: inverting the Euclidean Response w/ Maximum Entropy

Longitudinal



Transverse



q=400

500

600

700

Large Transverse Enhancement in Electron Scattering

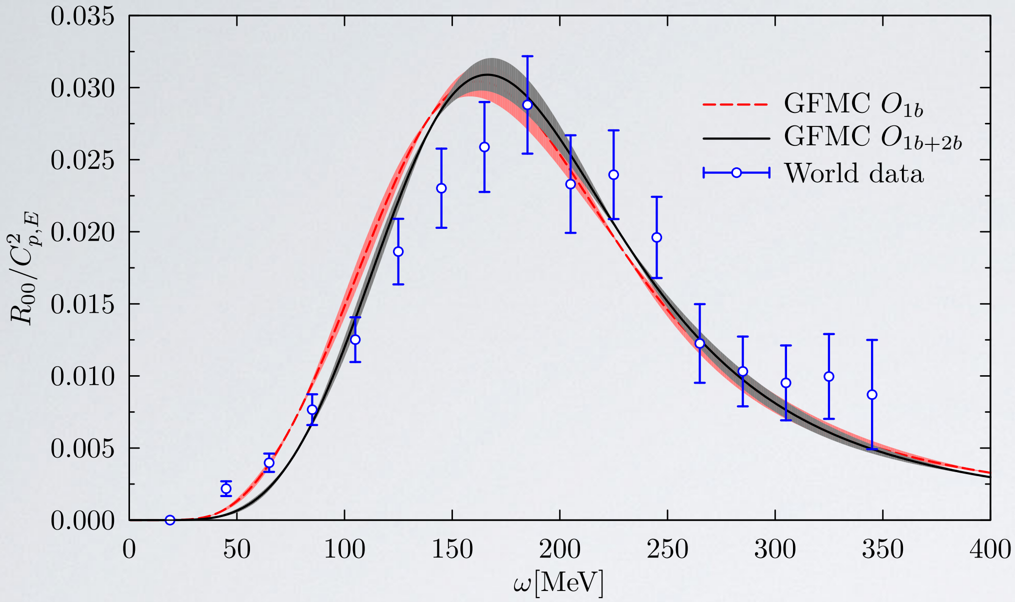
Experimental Data

1+2 Nucleon Currents

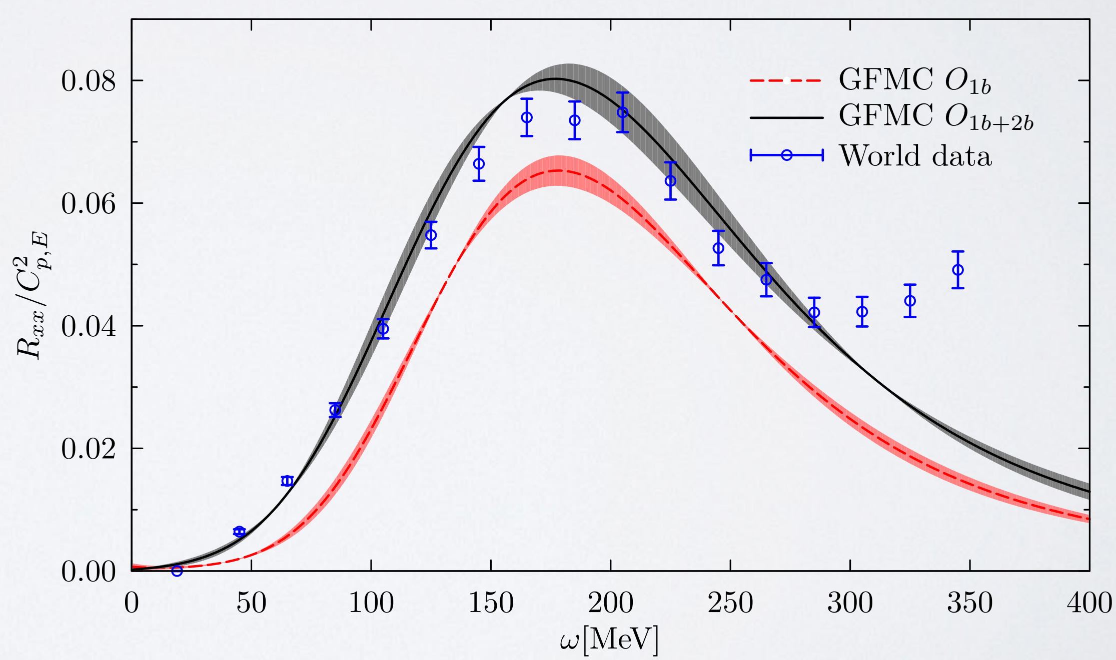
Single-Nucleon Currents

Lovato, et al: arXiv:1501.01981

^{12}C electron scattering inverting Euclidean Response - Lovato

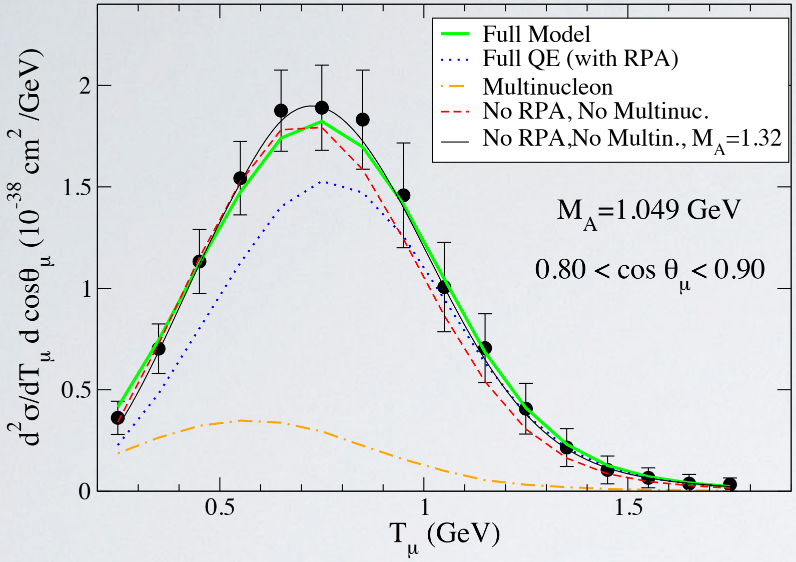


Longitudinal



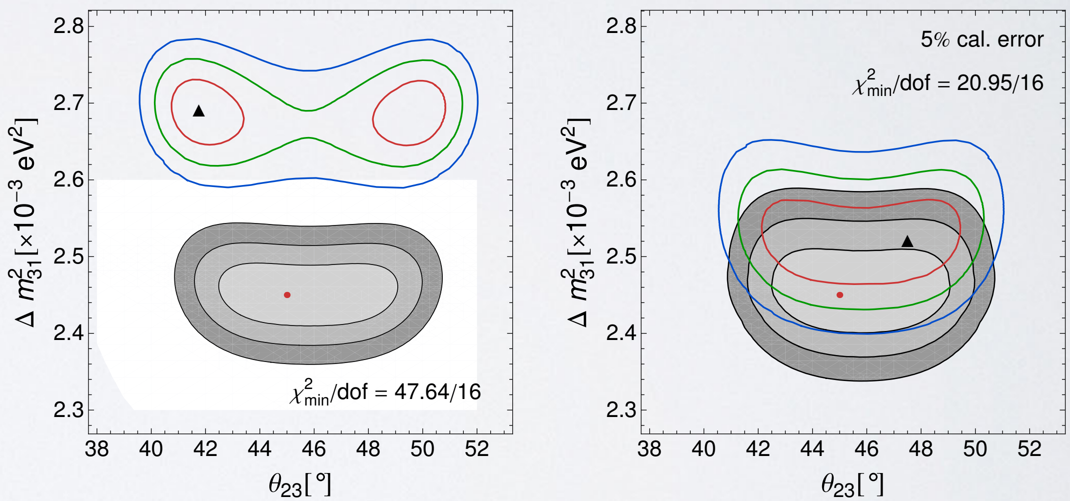
Transverse

Cross section models and Impact on Oscillation Parameters



Martini et al. (2011)

Using two different generators before improved models



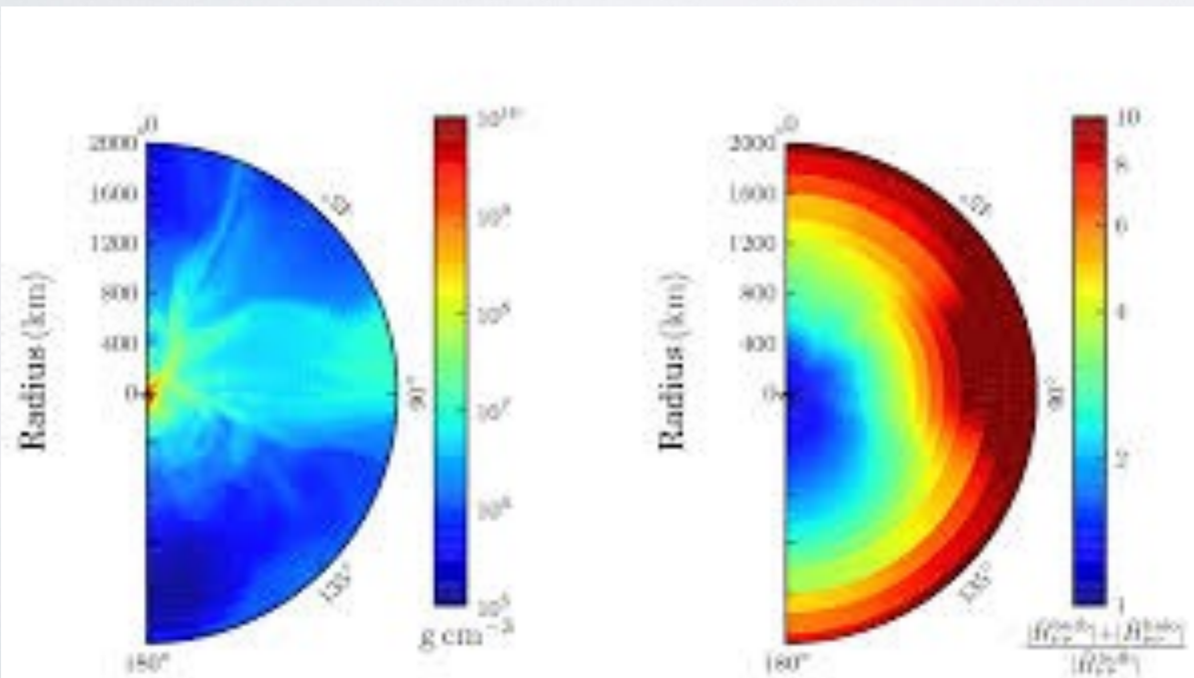
Coloma, et al. (2014)

see discussion in Benhar, et al: arXiv:1501.06448v1

may be overestimate of the problem

Present and Future Challenges

- Charged Current Scattering from ^{12}C
- Larger Nuclei (new US detectors use Argon)
- Relativistic Effects, Delta Resonances, …
- Incorporating Results into Event Generators (Classical)
- Lower Energy Scattering (Supernovae Neutrinos)
  - possible coherent neutrino-neutrino coherent evolution coupled with neutrino-nucleus scattering



Cherry, Carlson, Friedland, Fuller, Vlasenko, PRL 2012