Electron and Neutrino Scattering from Nuclei: What's Past is Prologue

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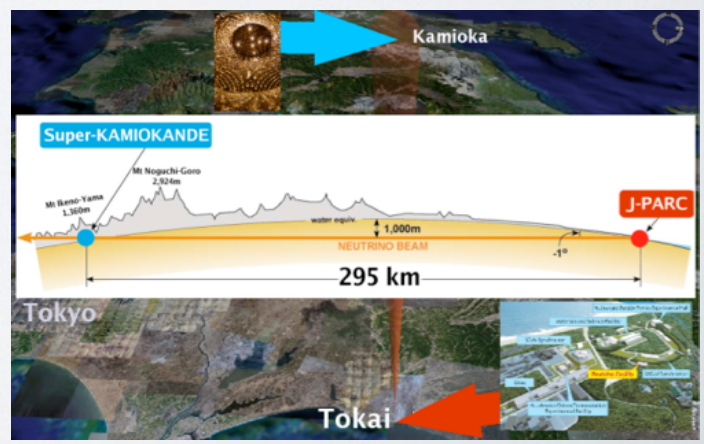
- Electron Scattering from Nuclei
  - Inclusive Scattering: Lessons learned
  - Recent expts: back-to-back nucleons
- Electrons versus Neutrino Scattering
  - EM and Weak Currents
  - Relations to other experiments: β decay, ββ decay, SN neutrinos
  - Summary and Outlook



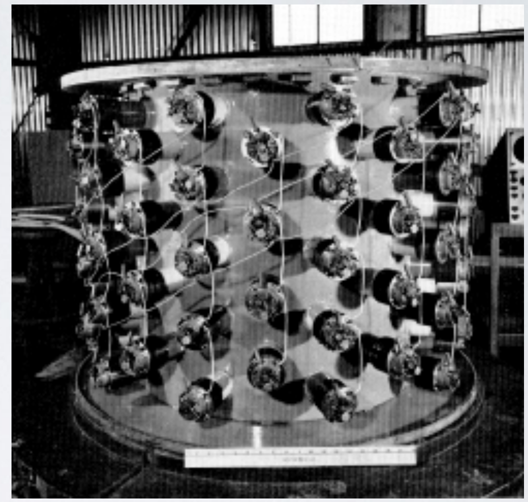
Neutrinos

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

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

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

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



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.

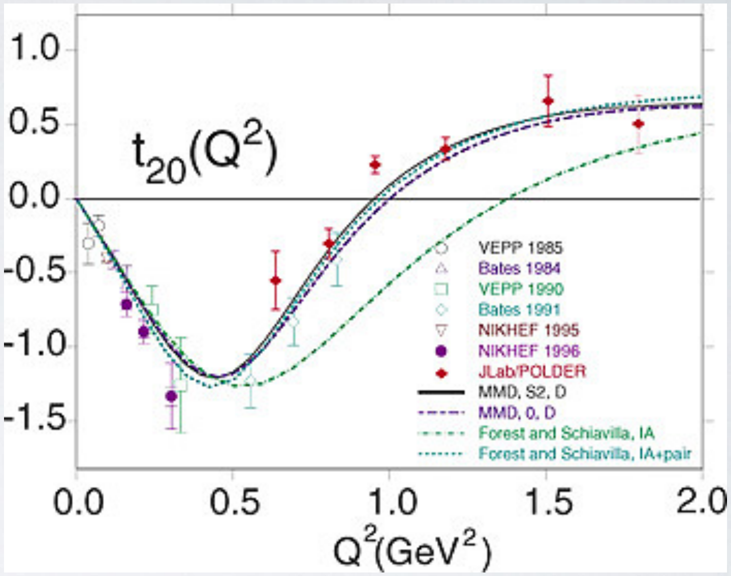
Reines and Cowan discovered the electron (anti-) neutrino. Later Lederman, Schwartz and Steinberger detected muon neutrino, receiving the Nobel Prize in 1988.

Nuclei: Interactions and Currents

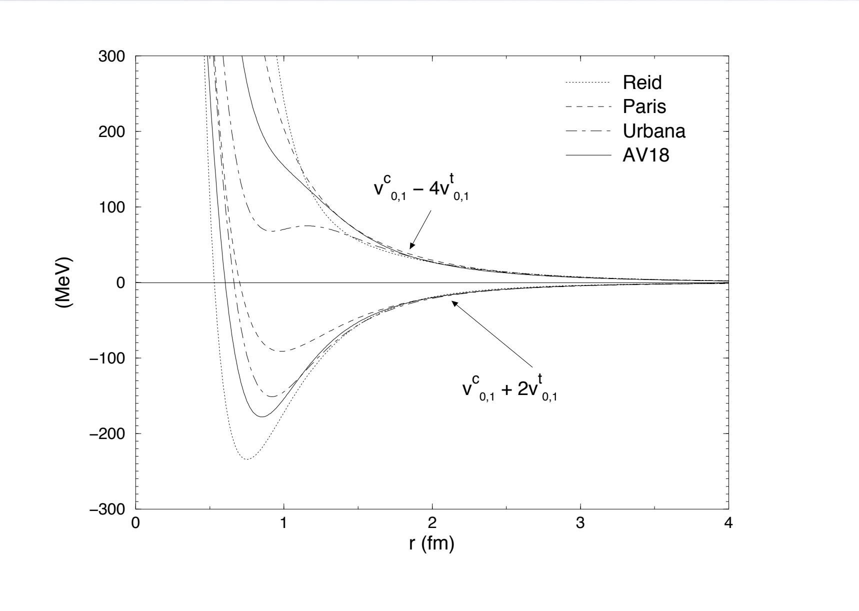
Non-relativistic nucleons w/ 2, 3-body interactions, currents

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

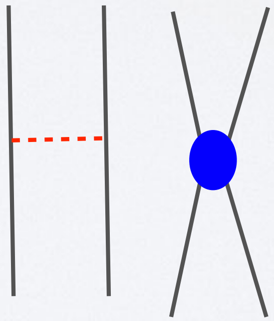
$$\mathbf{J} = \sum_i \mathbf{j}_{1;i} + \sum_{i<j} \mathbf{j}_{\mathbf{2;ij}} + \ldots$$

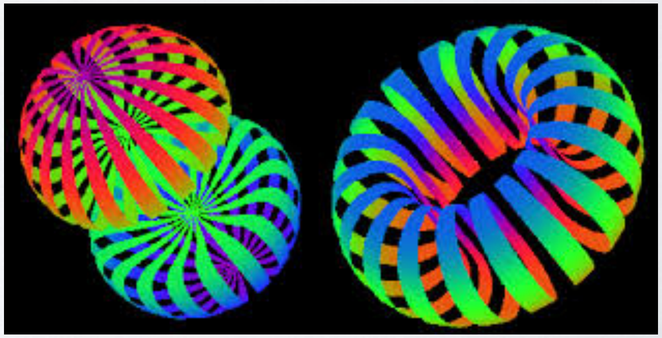


t20 experiment Jlab R. Holt



Deuteron Potential Models with Different Spin Orientations





Forrest, et al, PRC 1996

Light Nuclear Spectra

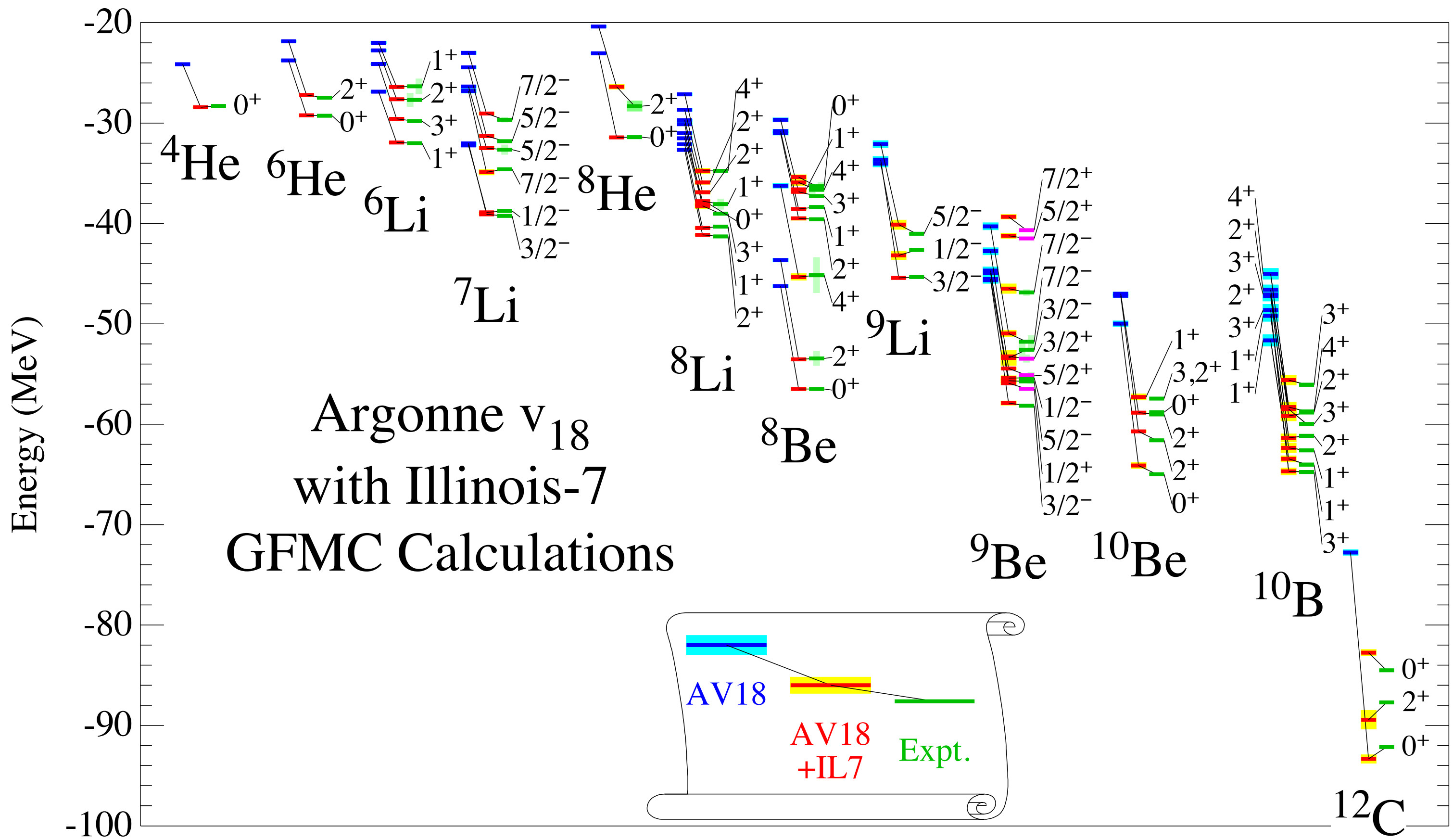
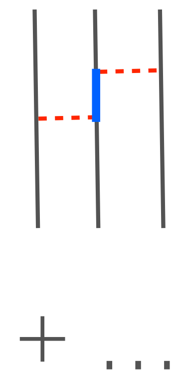


FIG. 2 GFMC energies of light nuclear ground and excited states for the AV18 and AV18+IL7 Hamiltonians compared to experiment.

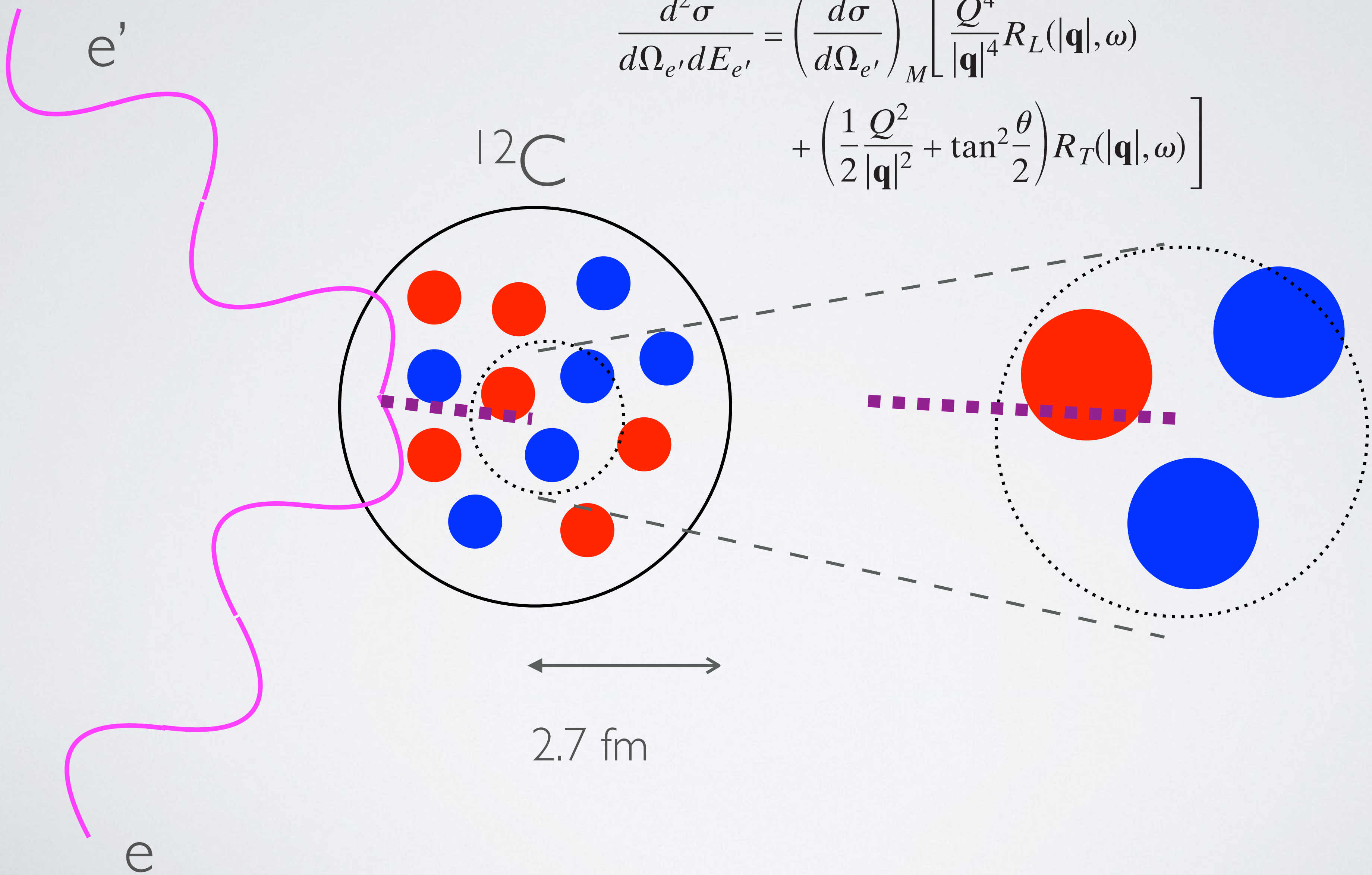


Carlson, et al, arXiv:1412.3081

Inclusive electron scattering,

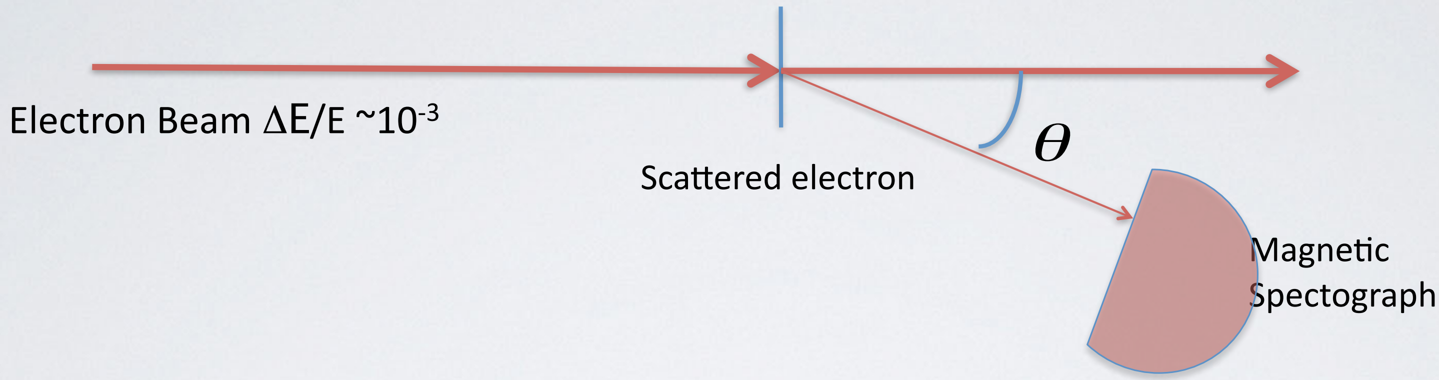
measure electron kinematics only

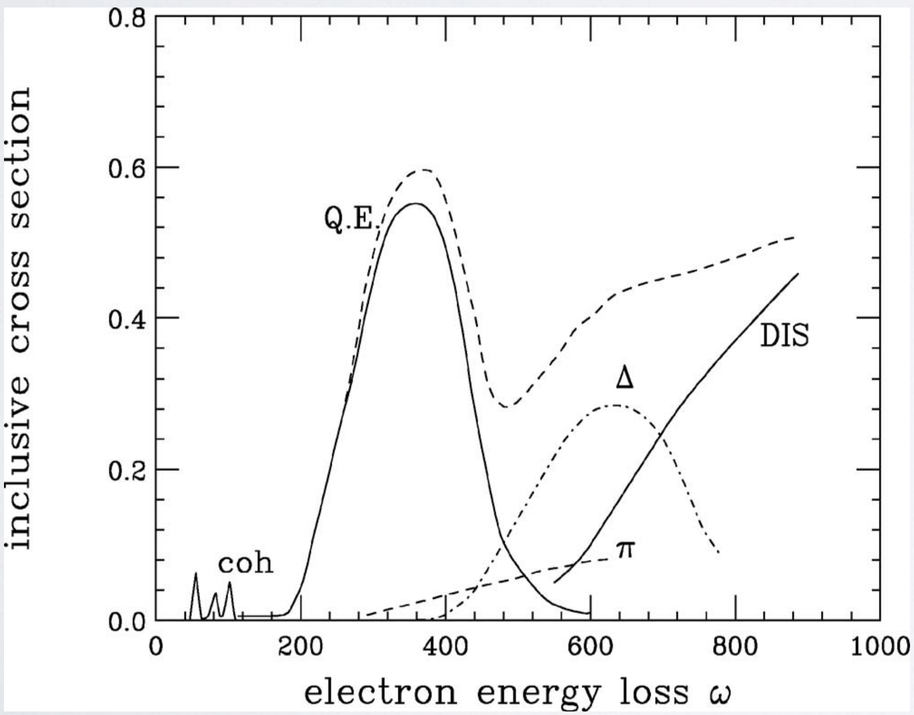
$$\frac{d^2\sigma}{d\Omega_{e'}\, dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4} R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega) \right]$$



Electron Scattering: Theorist's Idealized View

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

Electron Scattering: Longitudinal and Transverse Response

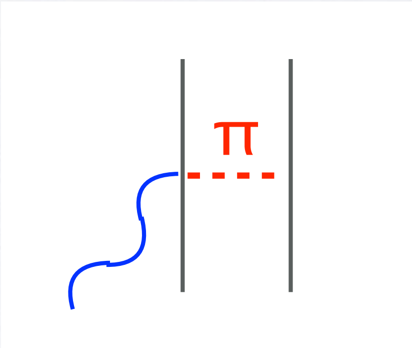
Transverse (current) response:

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

Longitudinal (charge) response:

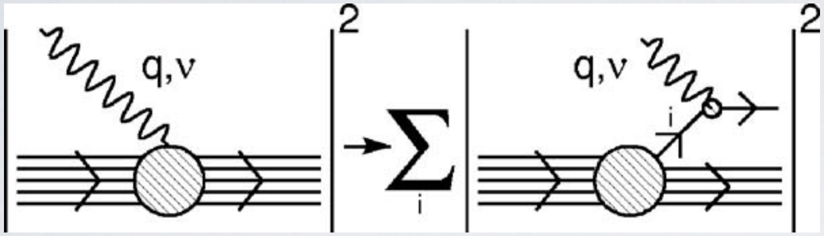
$$R_L(q,\omega) \;=\; \sum_f \langle 0|\; \rho^\dagger(q)\; |f\rangle\langle f|\; \rho(q)\; |0\rangle\; \delta(w-(E_f-E_0))$$

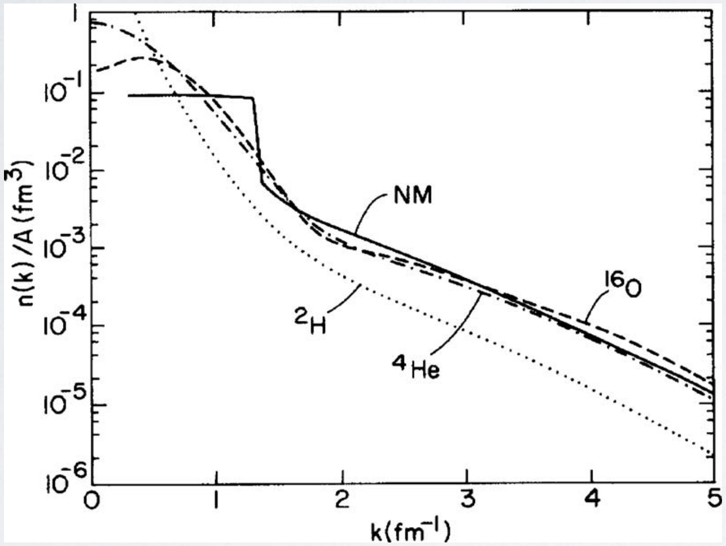
$$\mathbf{j} = \sum_i \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$



Two-nucleon currents required by current conservation
Response depends upon all the excited states of the nucleus
Might expect simplifications for q < 1/ k_F

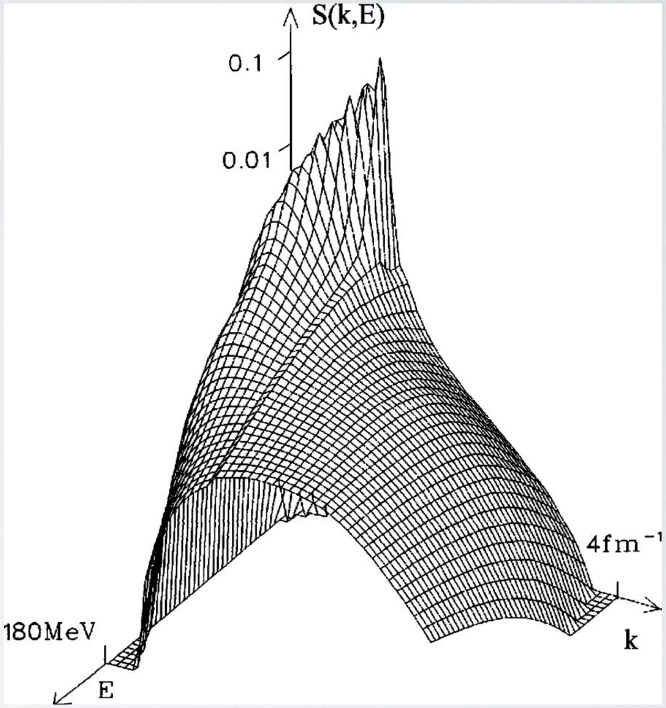
Momentum Distributions and Spectral Functions





Schiavilla, et al 1986, Benhar, et al 1993

Spectral Function in NM



Benhar, 1989

Impulse Approximation for quasi-elastic
incoherent sum over single nucleons
requires momentum distributions and/or spectral functions
broad applicability in neutron scattering, cold atom density response, …

One-body formulation gives equal longitudinal and transverse response
(once single-nucleon form factors divided out)

Simple view of inclusive QE scattering from nuclei

Charge distributions of different Nuclei:

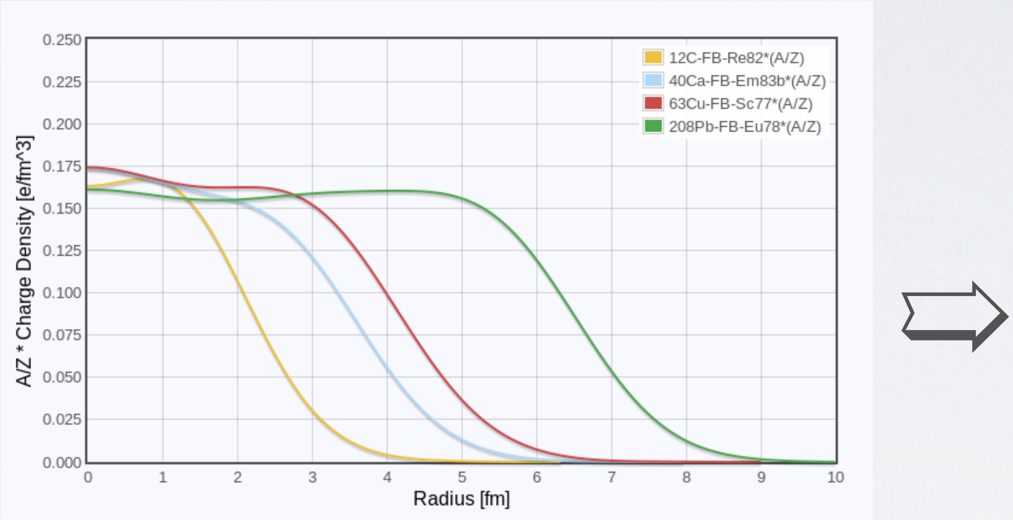
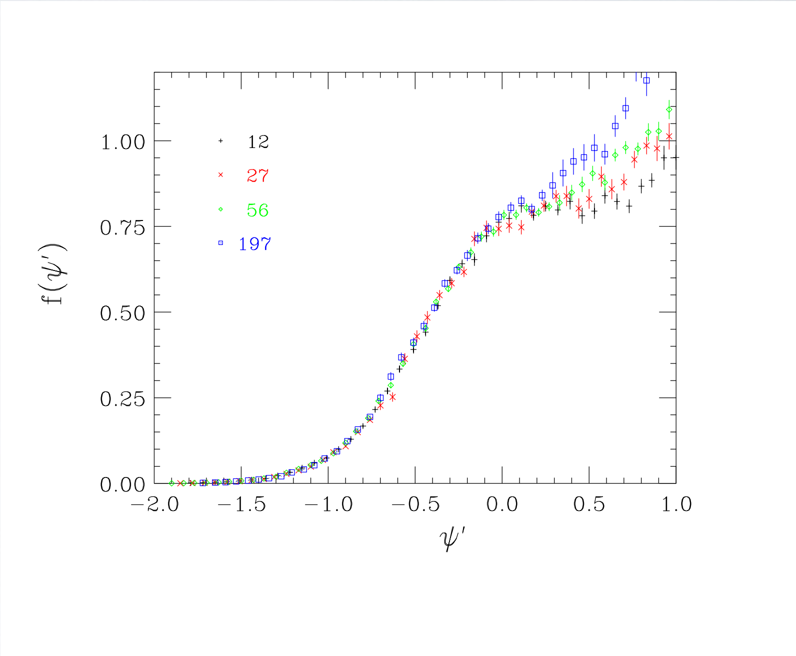


figure from faculty.virginia.edu/ncd
based on work of Hofstadter, et al.: Nobel Prize 1961

Scaling (2nd kind) different nuclei

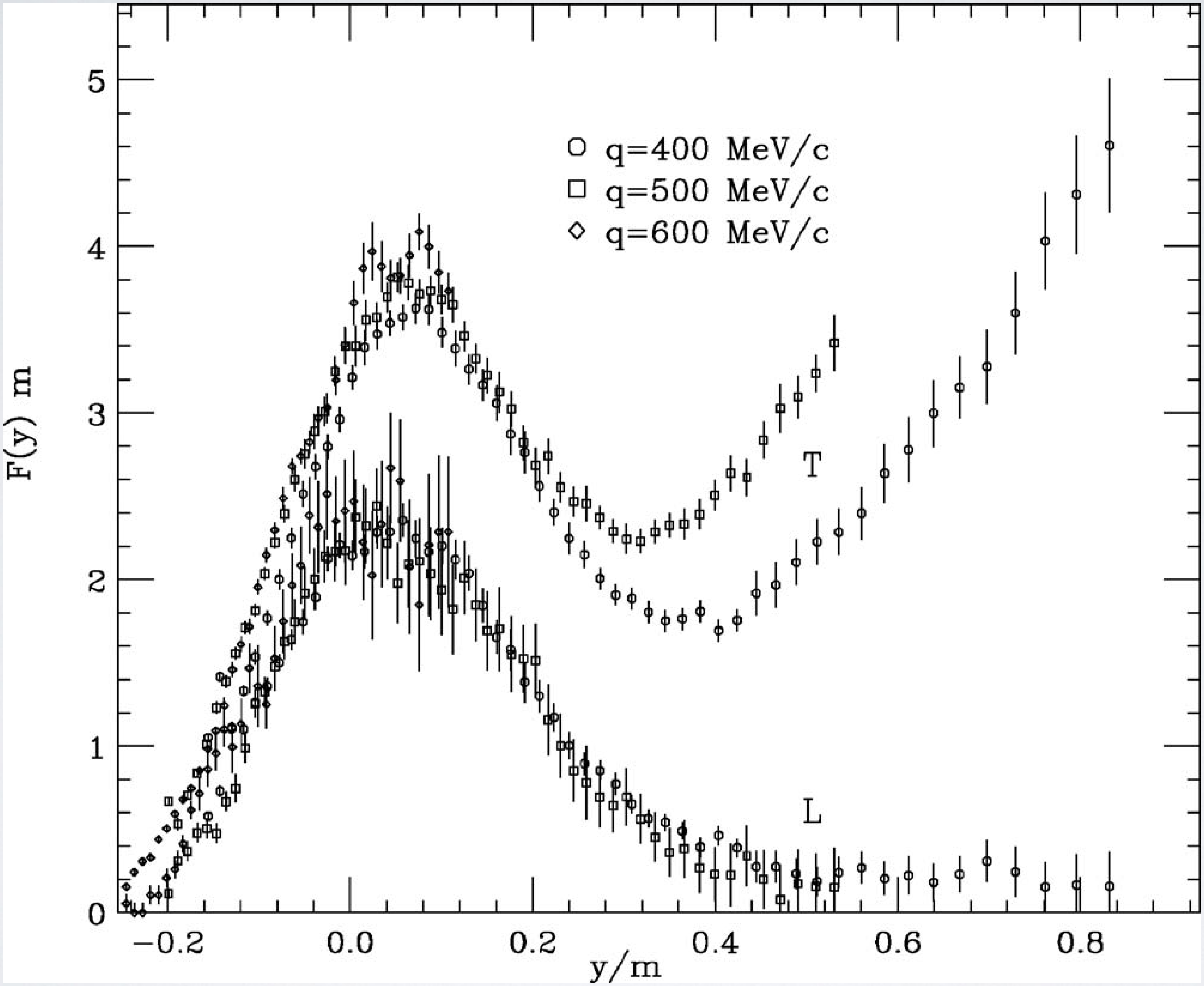


Slightly different k_F for different nuclei
Donnelly and Sick, 1999

Inclusive scattering measures nuclear properties at distances ~ π / q ≲ 1 fm
essentially independent of which nucleus!

Scaling ≠ Single-Nucleon Process

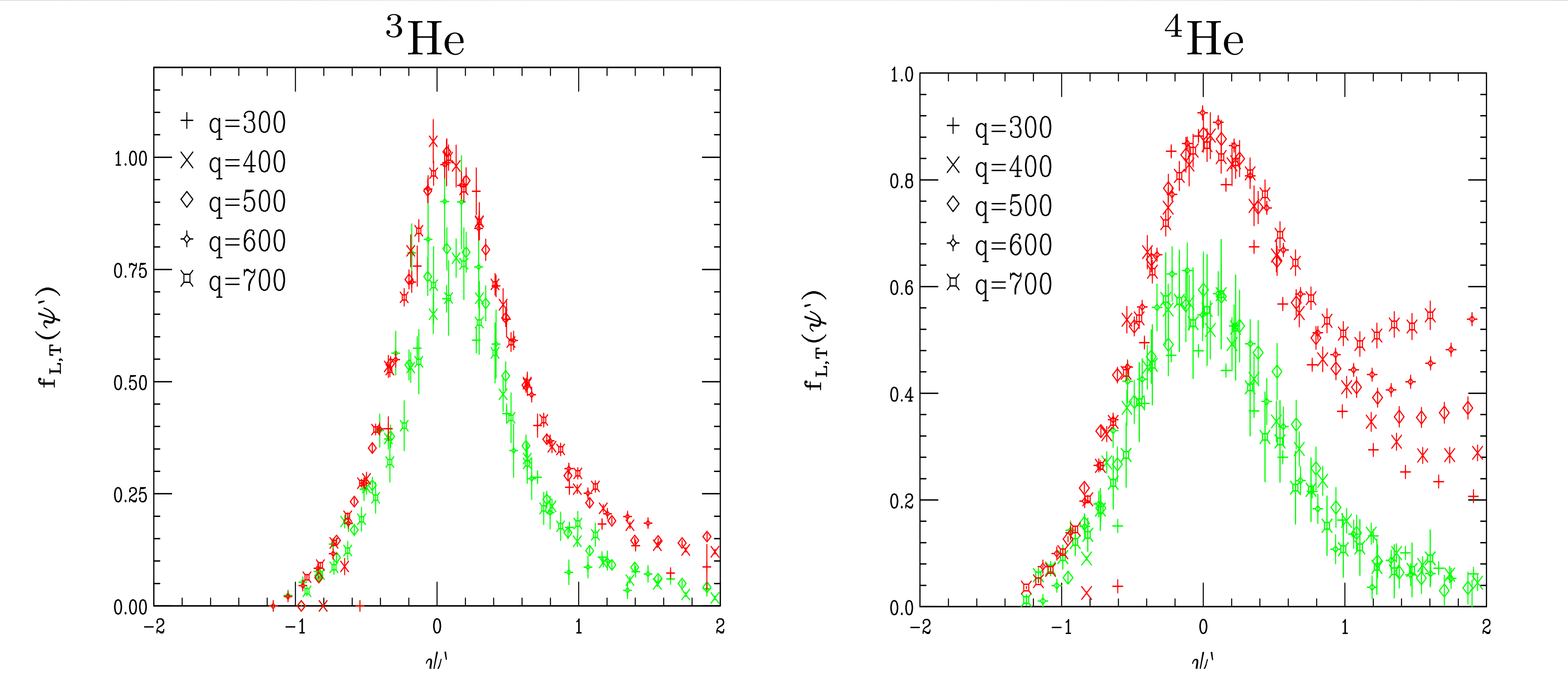
Longitudinal / Transverse separation in ^{12}C



from Benhar, Day, Sick, RMP 2008
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

Requires beyond single nucleon physics

^{12}C calculations:

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Nuclear Computational Low-Energy Initiative

computingnuclei.org

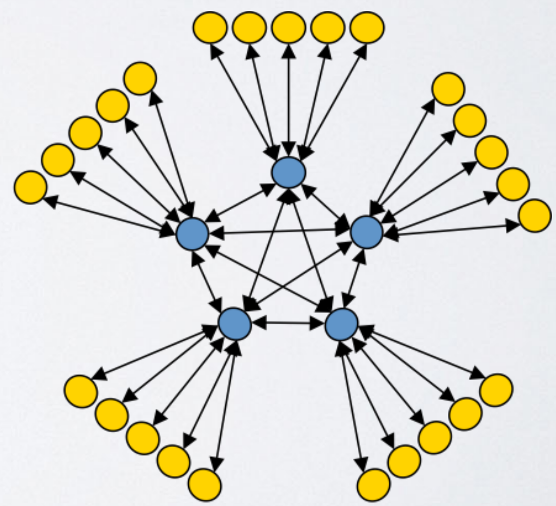
GFMC for ground-state
+ current correlation matrix elements

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

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

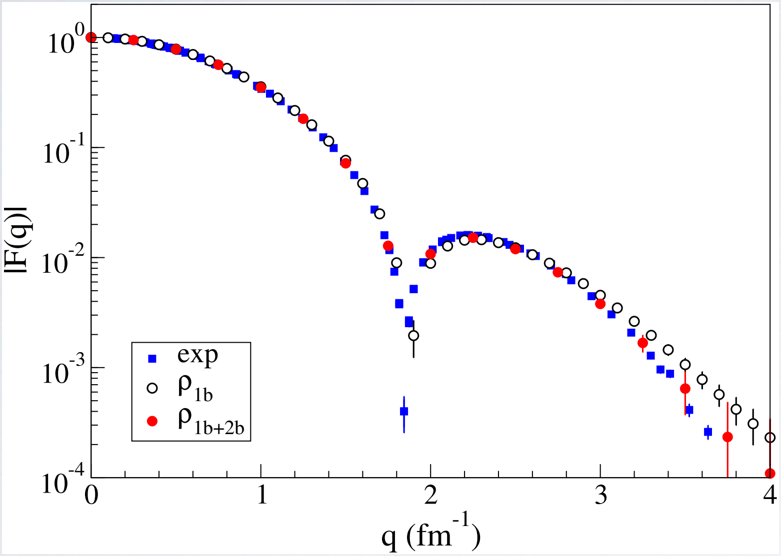
U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

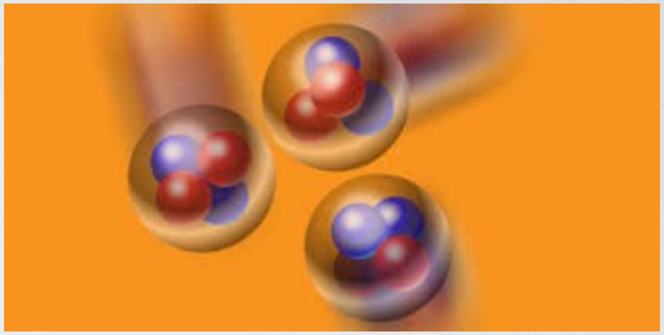
NNSA National Nuclear Security Administration

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

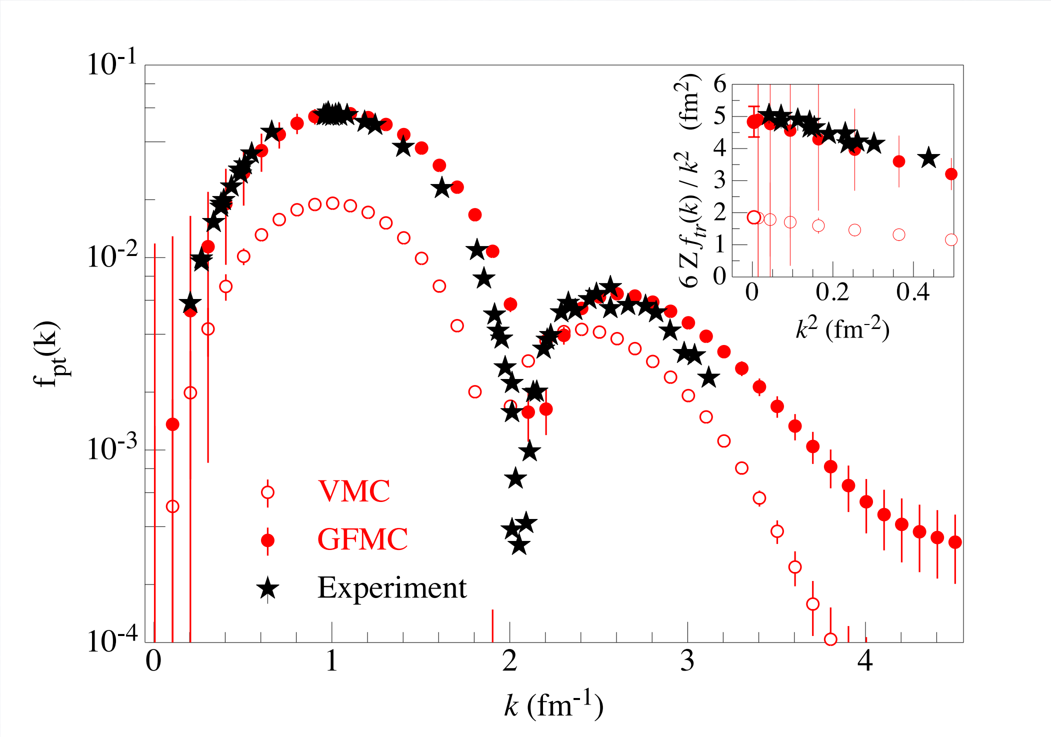
Currents and elastic/transition form factors

^{12}C elastic form factor





Hoyle state transition form factor



2 Nucleon charge operators
(relativistic corrections)
are small

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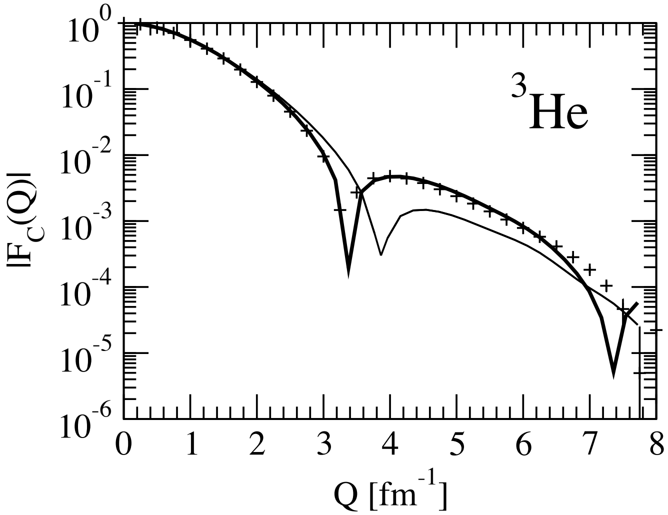
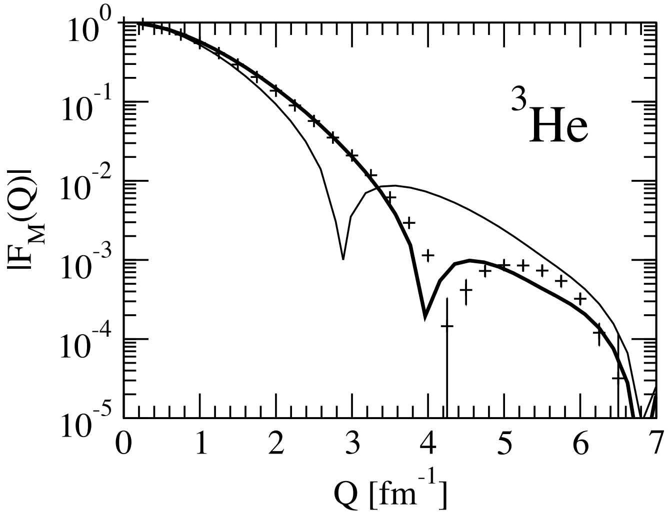
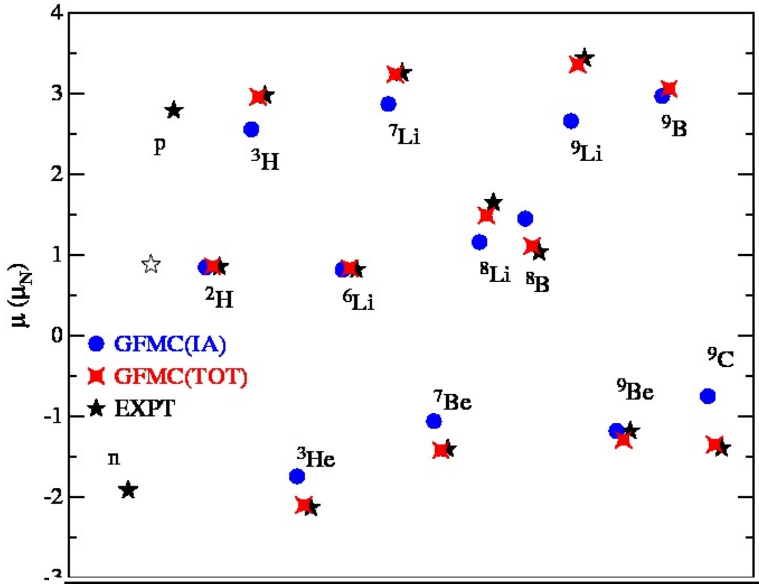
2-Nucleon Currents

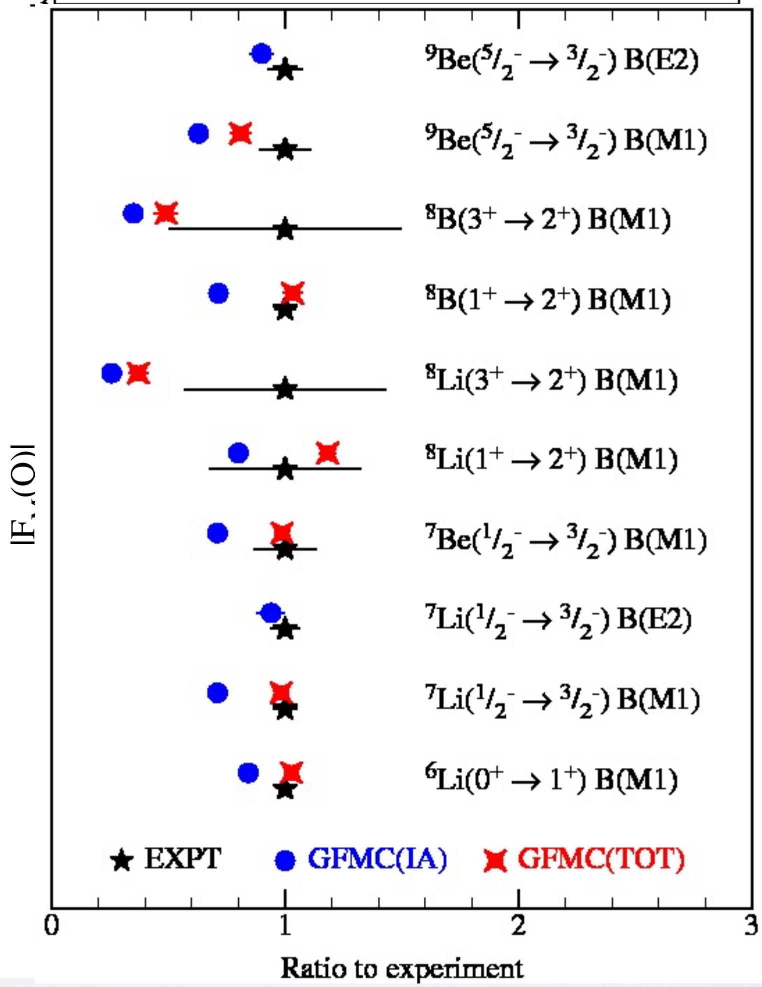
Form Factors







Magnetic Moments



EM Transitions

Nuclear Computational Low-Energy Initiative

Wiringa, Pastore, Schiavilla, et al

Path Integral Algorithm: $\Psi_0 \; = \exp\left[-H\tau\right] \, \Psi_T$

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

Easy to calculate Sum Rules: ground-state observable

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

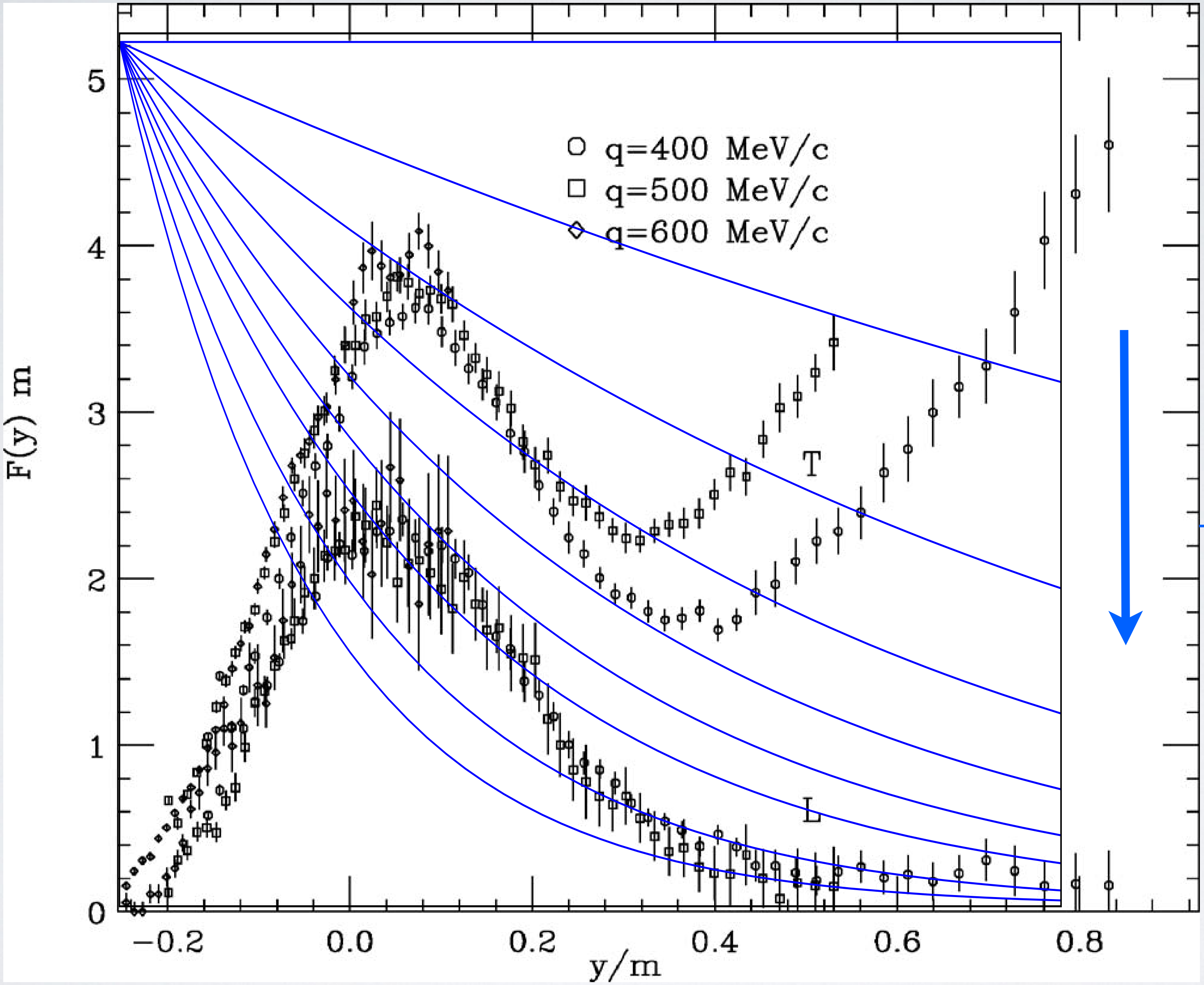
Imaginary Time (Euclidean Response)
statistical mechanics

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

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

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

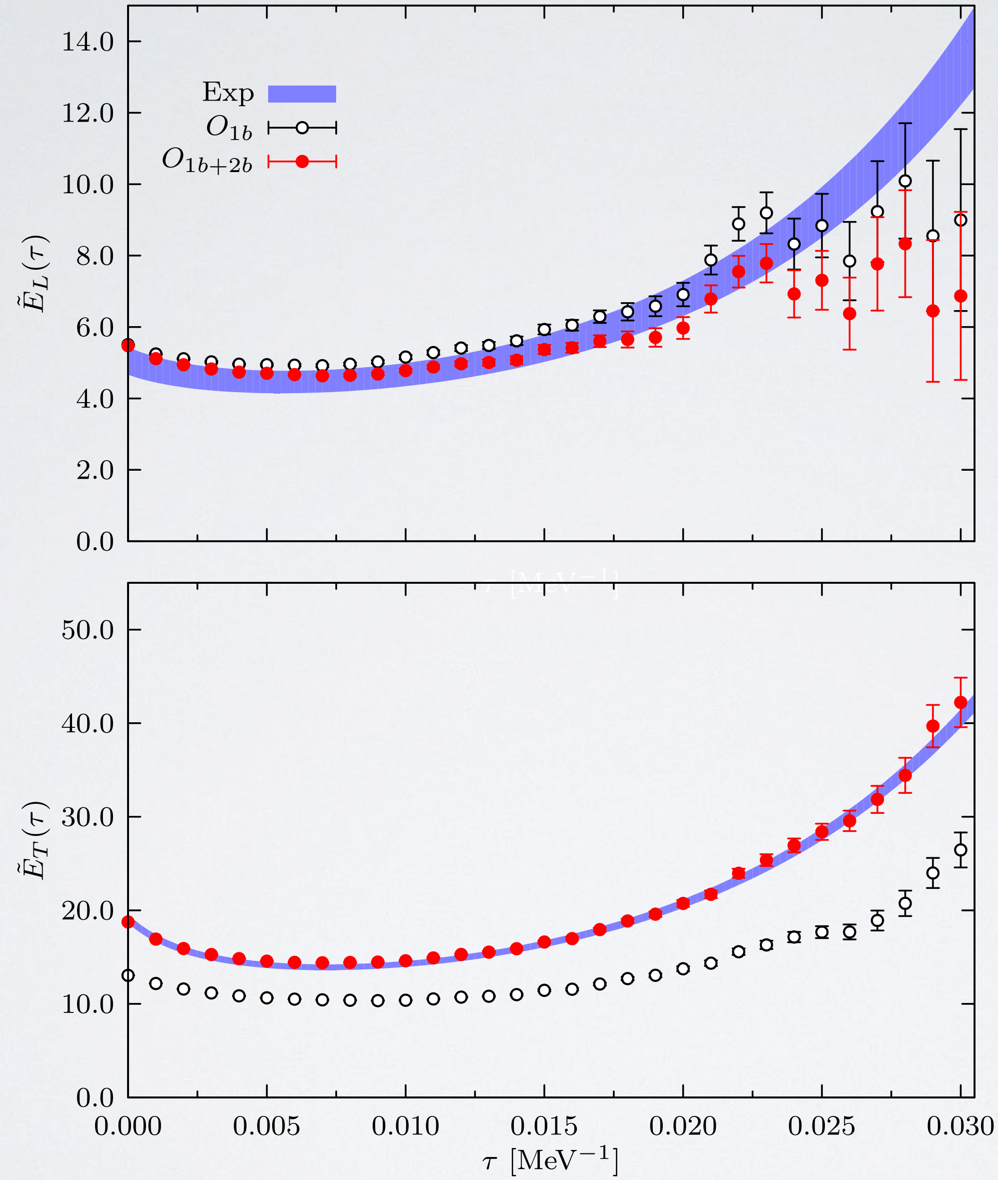
Euclidean Response



τ = inverse Temperature

Sum rule → elastic FF^2 w/ increasing τ

^{12}C Euclidean Response: electron scattering

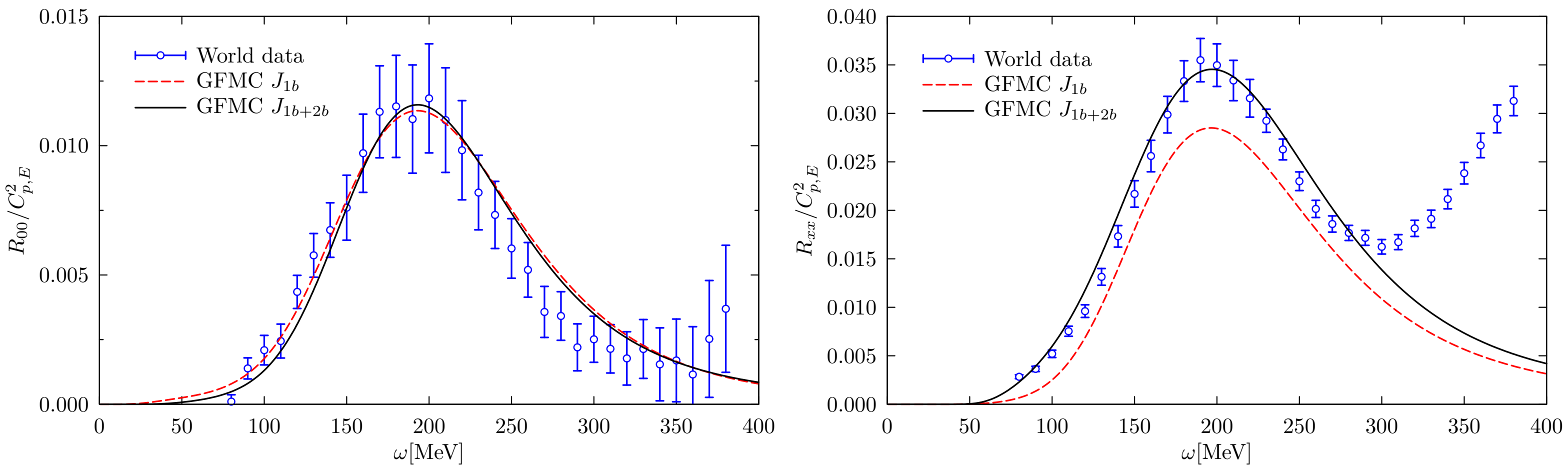


Longitudinal

Transverse: enhancement from 2-nucleon current

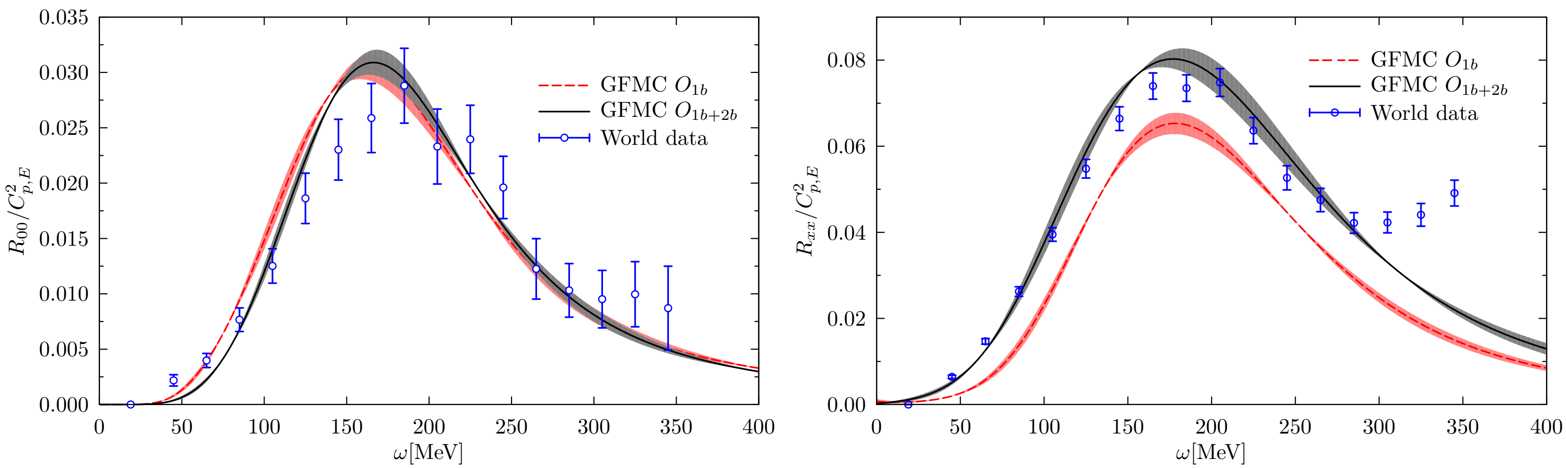
Lovato, et al, arXiv:1501.01981

Electron Scattering in Helium and Carbon Maximum Entropy for Inversion (Lovato)



Electromagnetic Longitudinal and transverse in ^{4}He.

Lovato, Gandolfi, Carlson, Pieper, Schiavilla, PRC (2015))

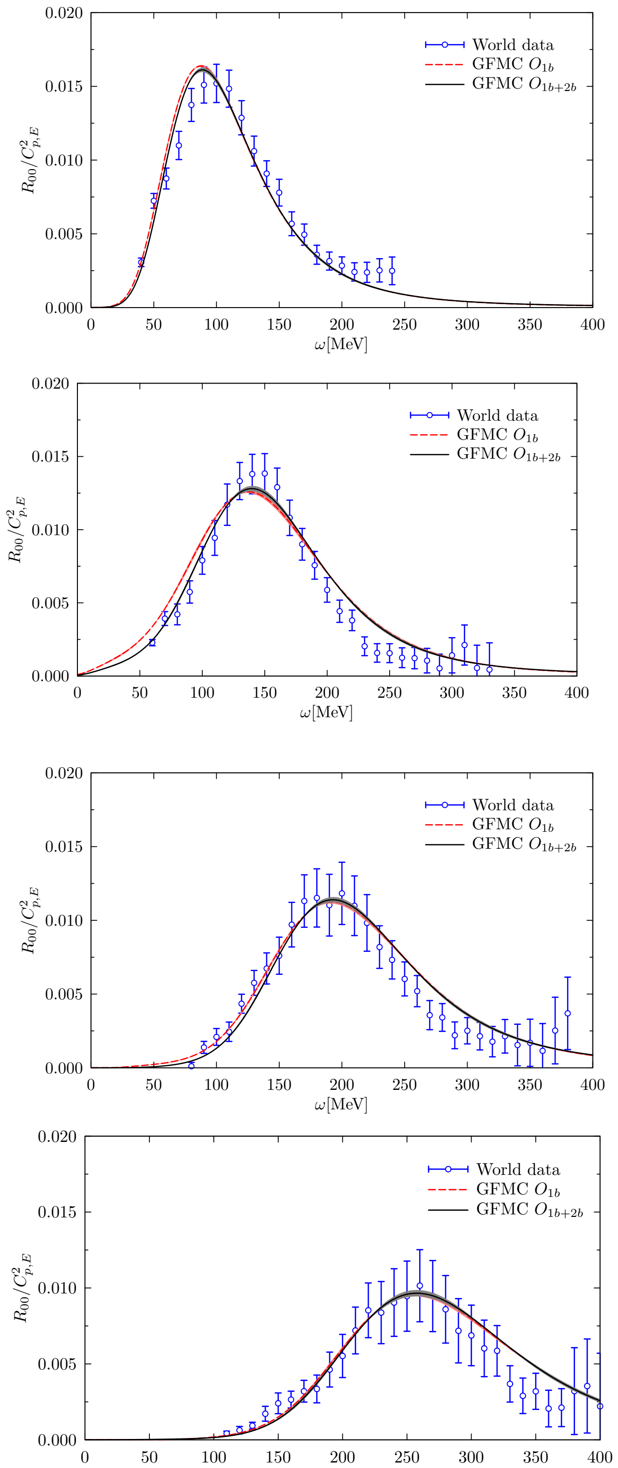


Preliminary: Electromagnetic Longitudinal and transverse in ^{12}C.

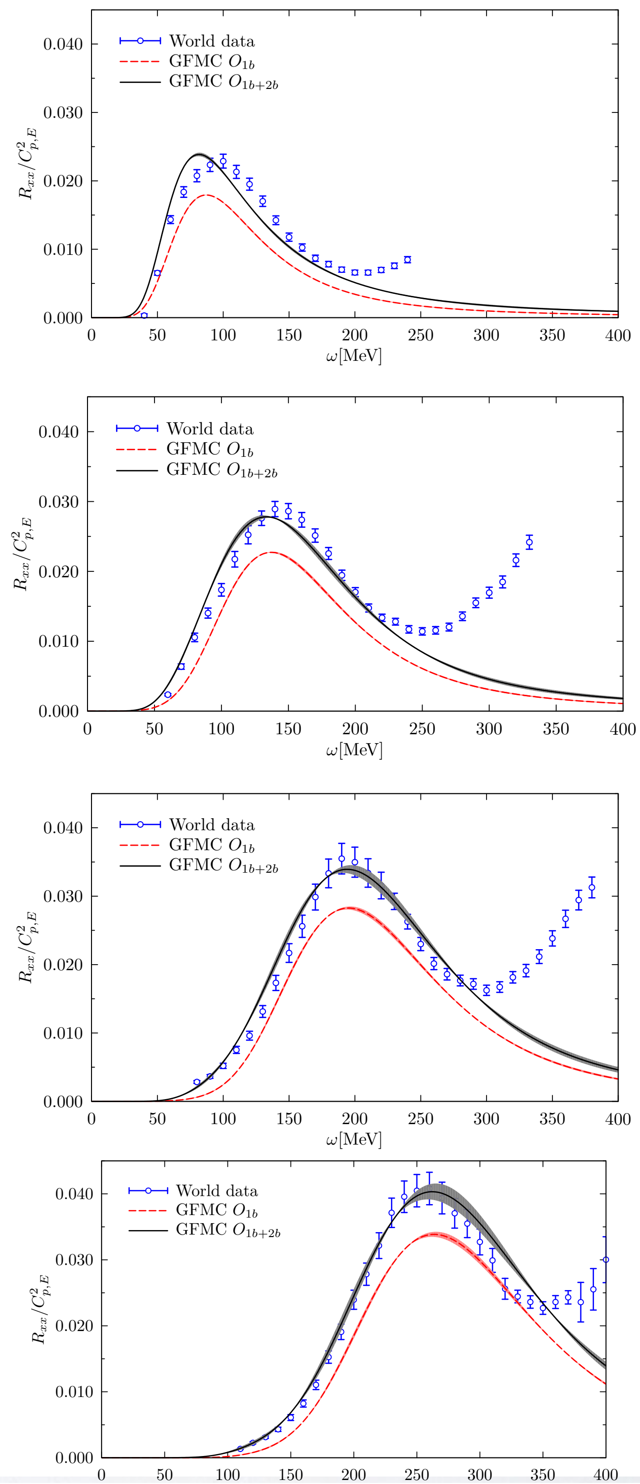
Lovato, Gandolfi, Carlson, Pieper, Schiavilla, (2016))

^{4}He EM

Longitudinal



Transverse



q=400

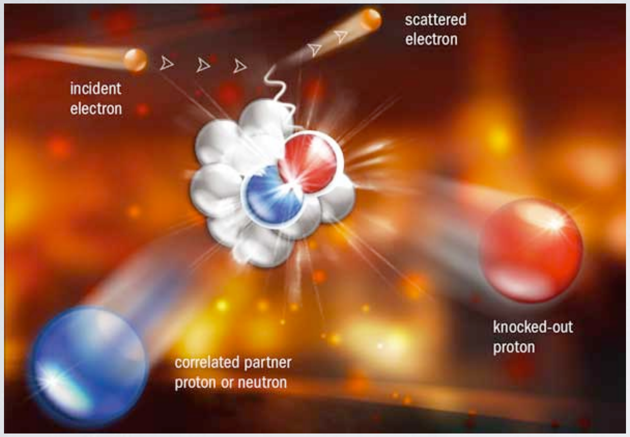
500

600

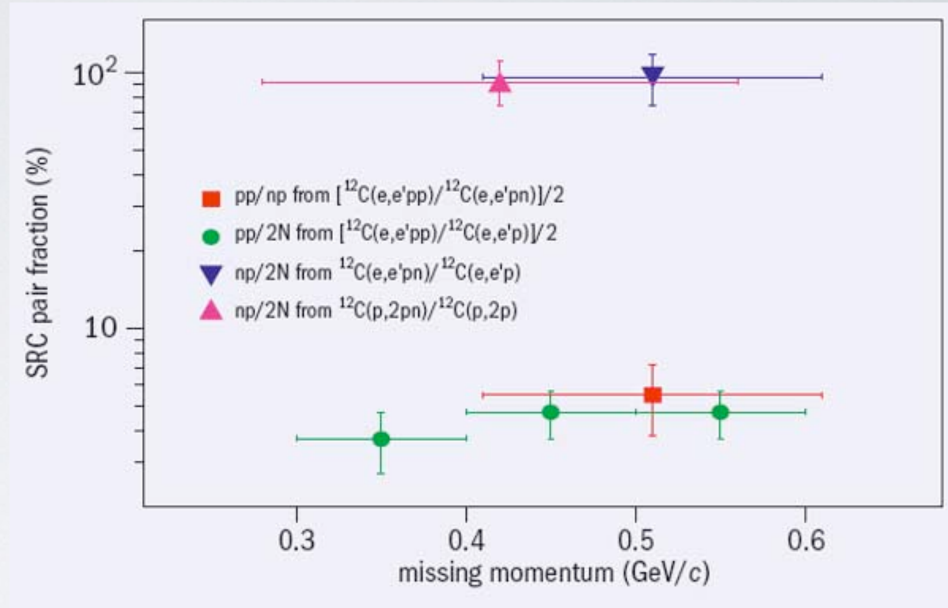
700

Lovato, 2015 (prelim)

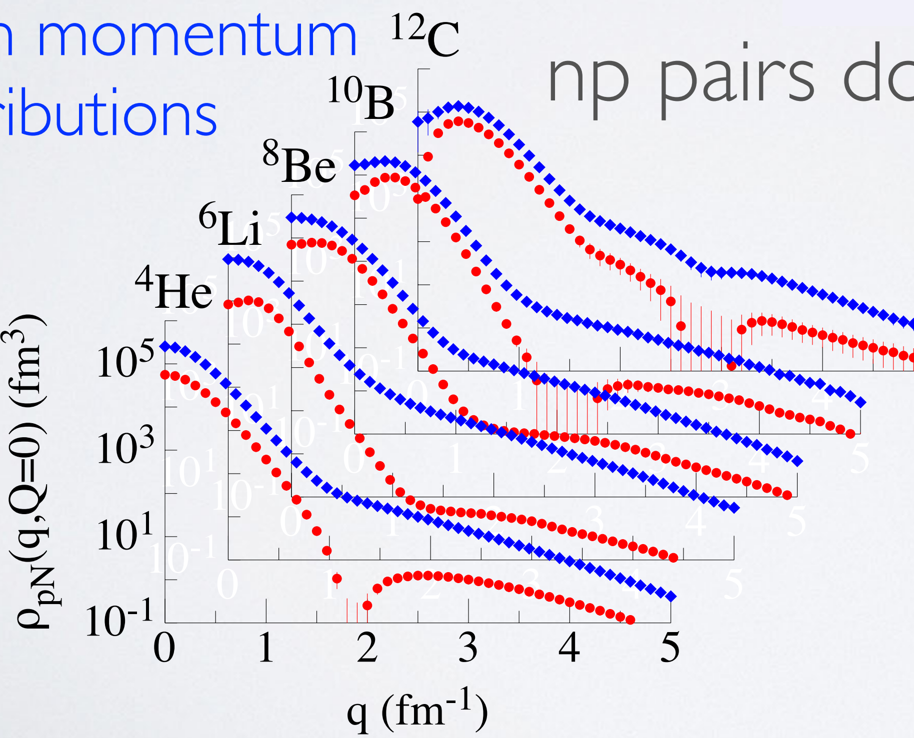
Back to Back Nucleons: Jlab experiments



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.



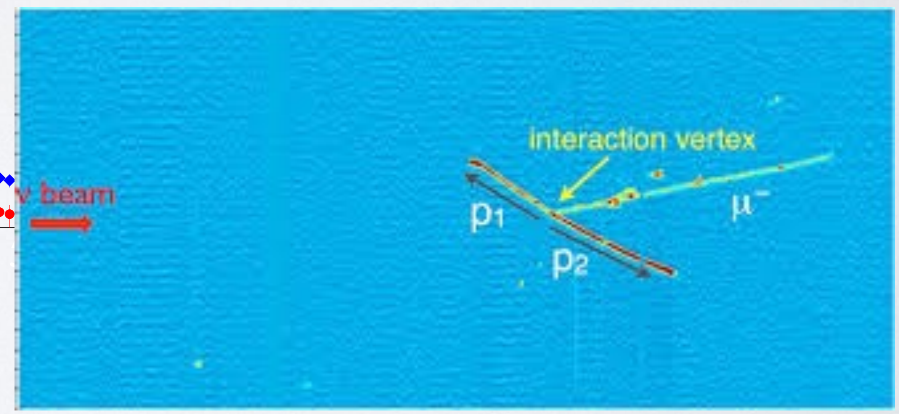
2-nucleon momentum distributions



np vs. pp

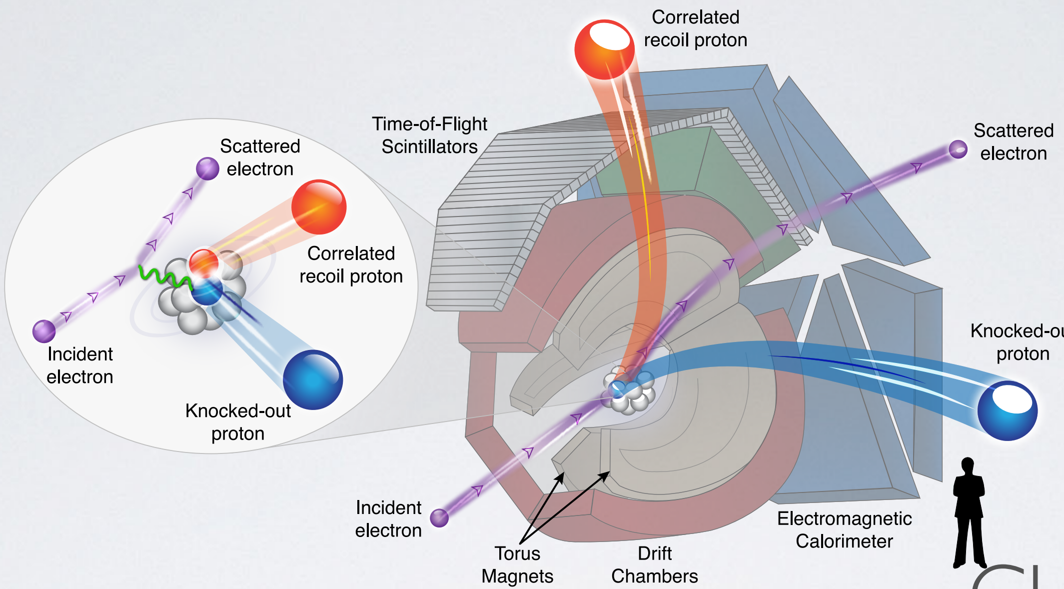
Carlson, et al, arXiv:1412.3081

np pairs dominate over nn and pp

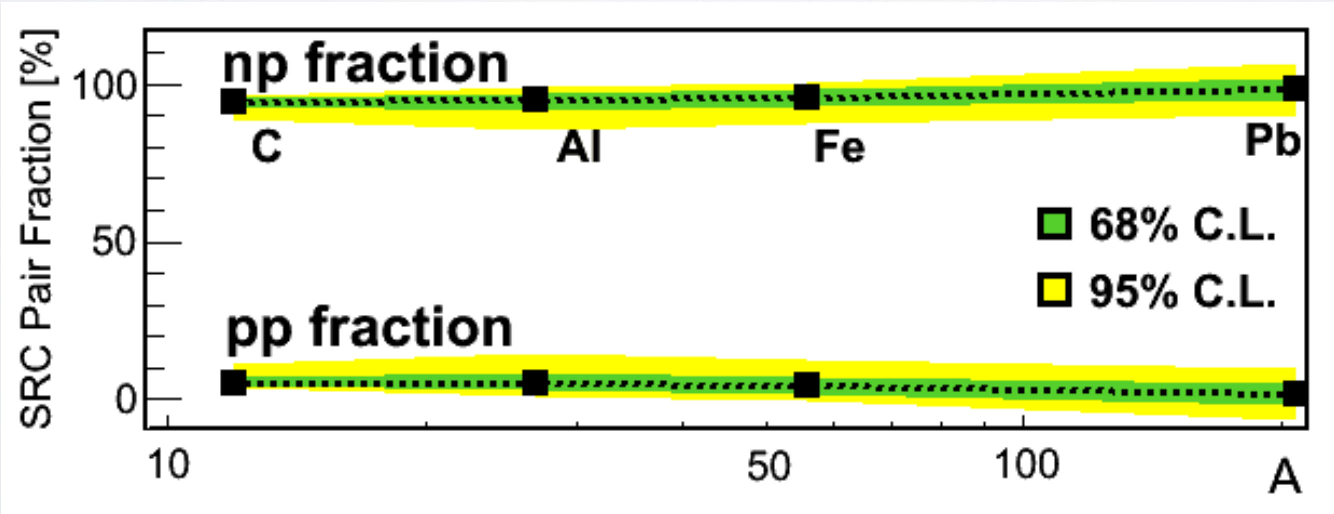


Argoneut

Recent Experiments: Heavy Nuclei



CLAS (JLab)



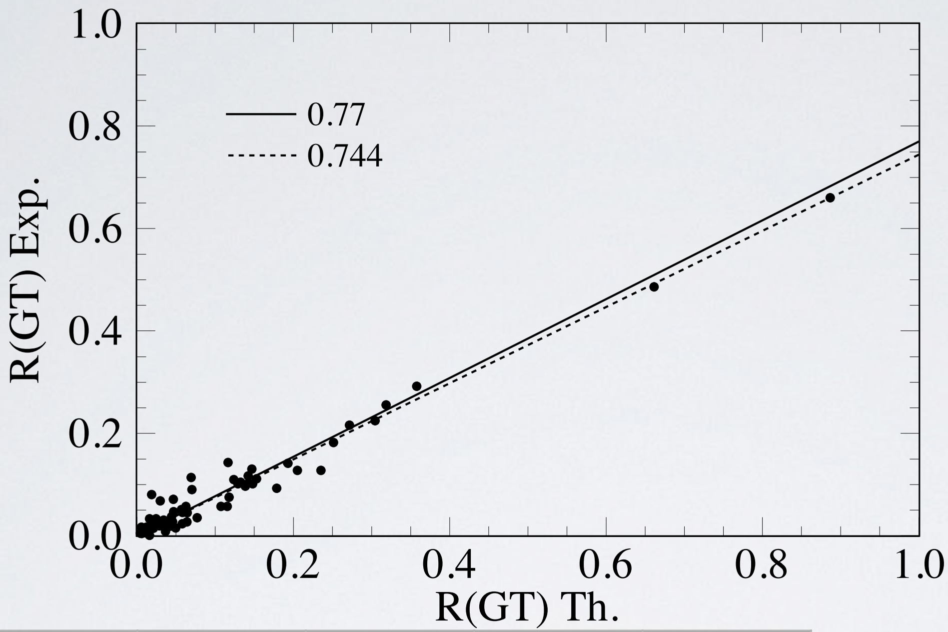
Hen, et al
Science
(2014)

Neutrinos and Nuclei

Solar Neutrinos
Beta Decay
Reactor Neutrinos
Atmospheric Neutrinos
Accelerator Neutrinos
Astrophysical Neutrinos (Supernovae, …)
Double-Beta Decay

All to some degree require knowledge of neutrino interactions with nuclei (different kinematics)

Axial Currents at Low Momentum Transfer: Beta Decay



Shell Model Calculations of Beta Decay typically require a quenching (reduction) of g_A by ~ 0.75

Martinez-Pinedo and Poves, PRC 1996

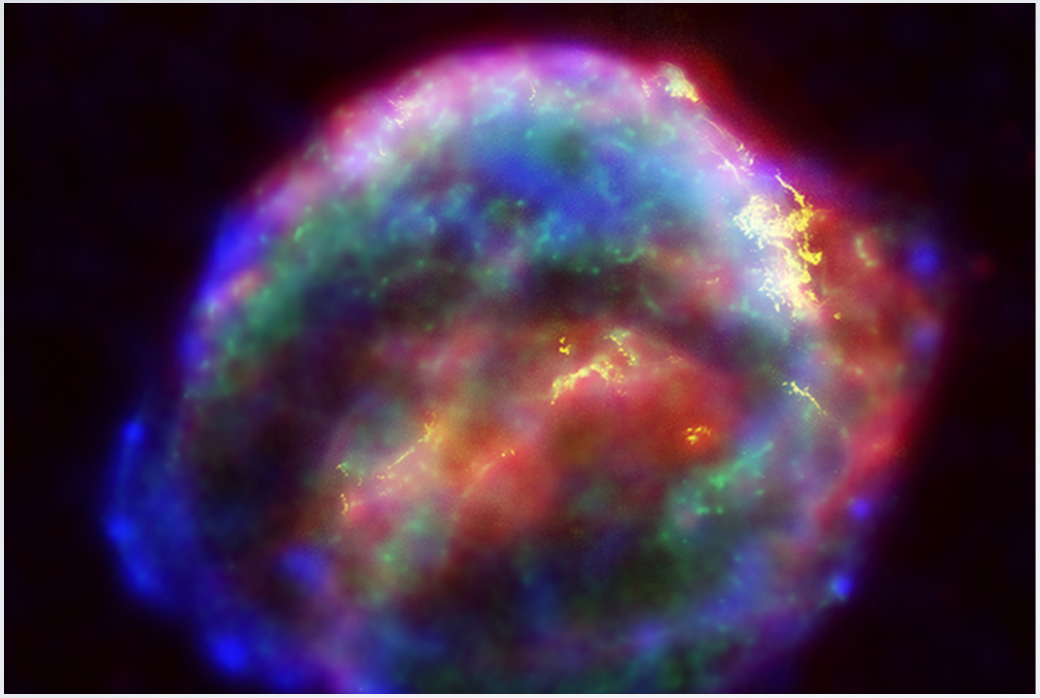
	Simple	1-Body current	1+2 current	Exp⊙
A=3	2.45	2.27	2.28*	2.28
A=6	2.4	2.15	2.19	2.2
A=7	2.58	2.29	2.39	2.4
A=10	2.45	2.06		2.34

Smaller (~ 10%) quenching reproduced in light nuclei

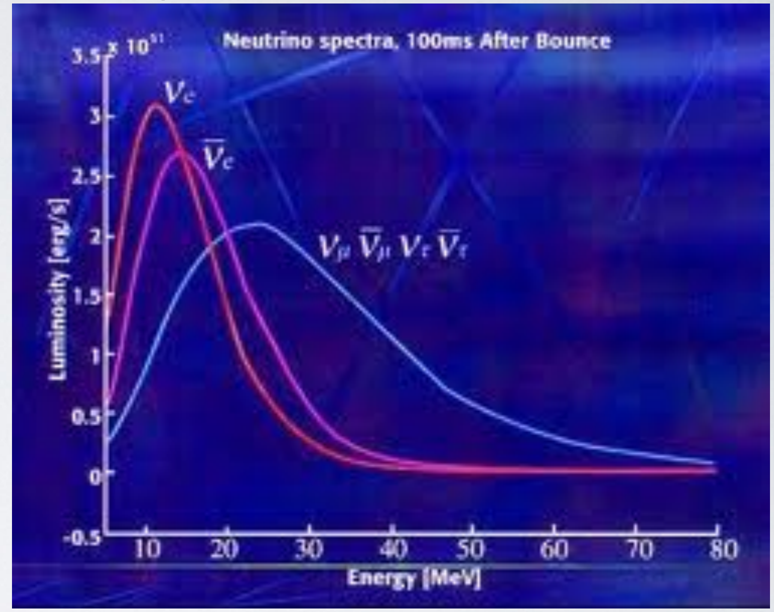
(preliminary)

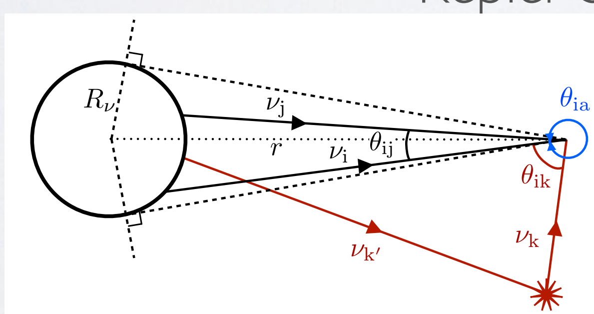
Intermediate q, E : Supernovae and Astrophysical Neutrinos

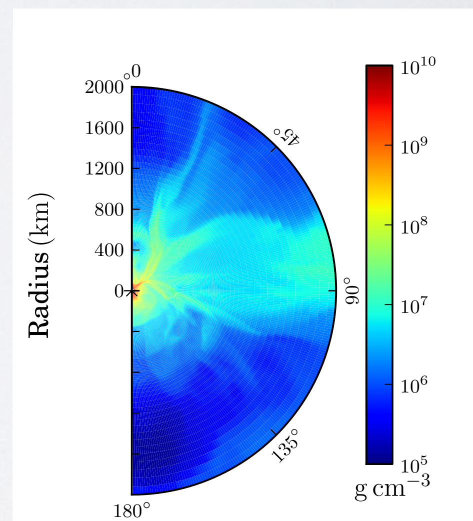
Different Sources, time dependence, different epochs



Kepler Supernova







Coherent Oscillations, MSW in turbulent regime, …

Can we make r-process nuclei in supernovae ?

Intermediate q: Neutrino Scattering from ^{12}C (LSND) and Astrophysical Neutrinos Theory

Hayes and Towner, PRC, 1999

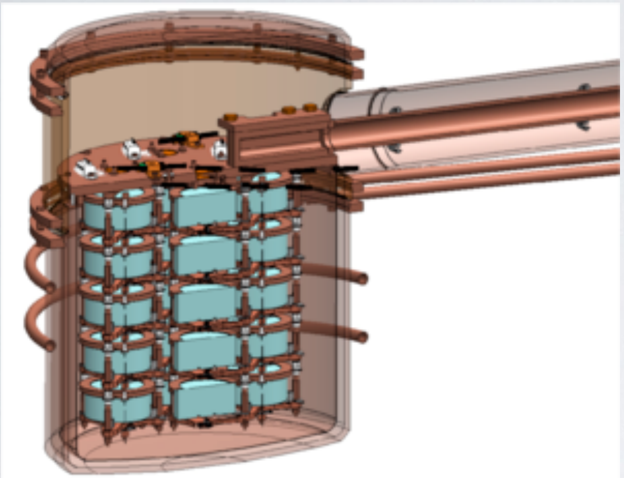
	Muon neutrino DIF	Electron neutrino DAR	Muon Capture	Photo-absorption
Shell Model	13.8	12.5	42.2	23.6
Exp	12.4(2)	14.4(4)	39.0(1)	21(2)

Astrophysical Neutrinos on ^{4}He Theory
w/ 2 nucleon currents
Gazit and Barnea, PRL 2007

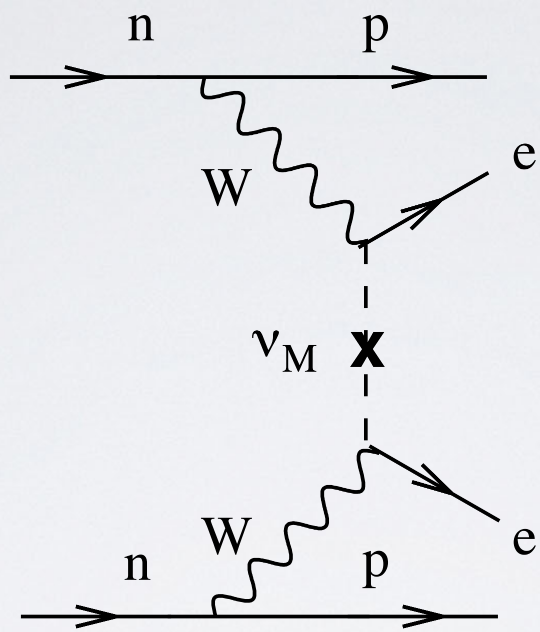
Little evidence for quenching (or enhancement) for 30-100 MeV neutrinos

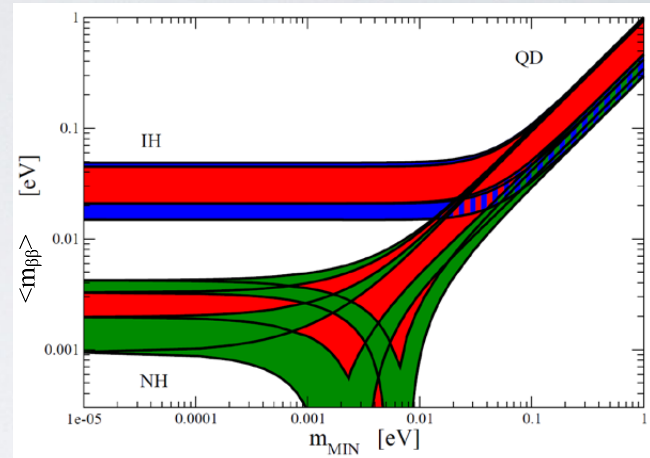
Neutrinoless Double Beta Decay

Rate: Absolute Mass Scale



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)

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

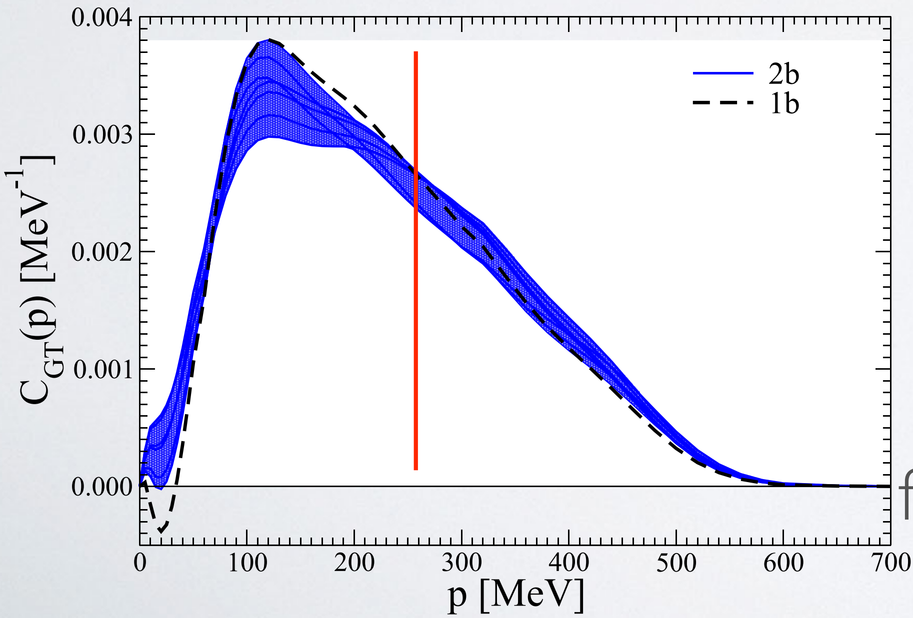
$$M_{0V}^{GT} = \langle f| \sum_{i<j} \frac{R}{r} \sigma_i \cdot \sigma_j\ \tau_i^+ \tau_j^+ |i\rangle$$

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

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

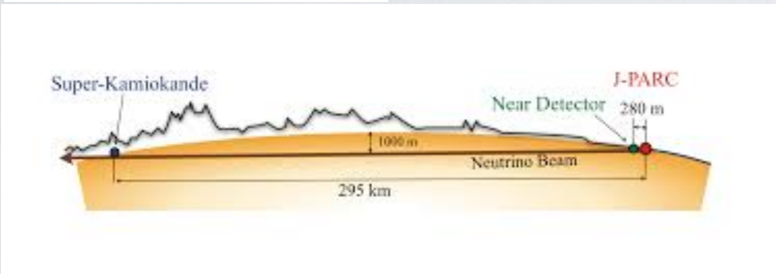


Different from single-beta decay
and from inclusive scattering

momentum dependence of ME
from Engel, Simkovic Vogel (2014)

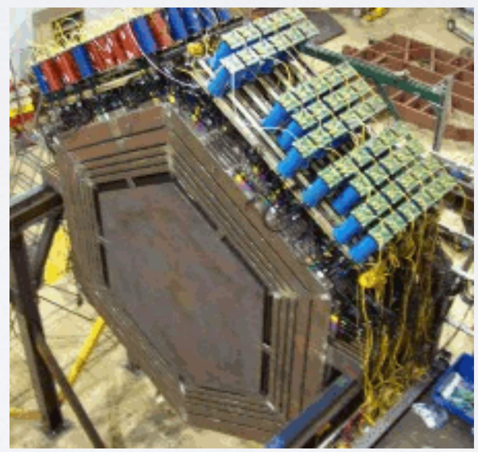
Accelerator Neutrinos

T2K

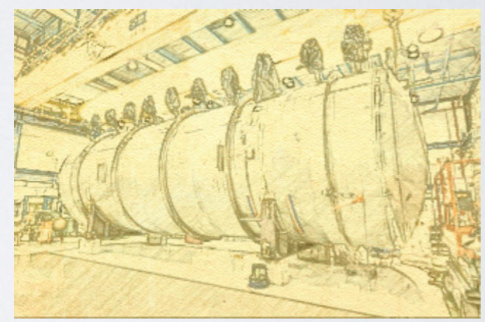


MINOS

SuperK



MINERva



MicroBooNE

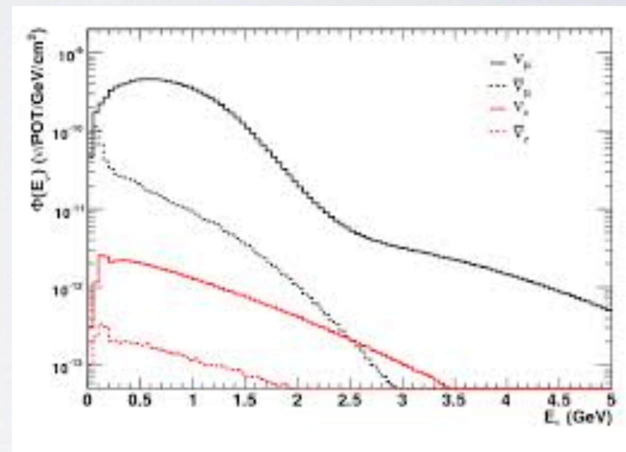
Advantages: Control over Energy, flux

neutrino 'beams' can be sent over long distances

Theorist's Idealized Neutrino Experiment

Monochromatic neutrino (or anti-neutrino) beam
with well-characterized flavor
detected at at least 2 distances w/ different flavors resolved

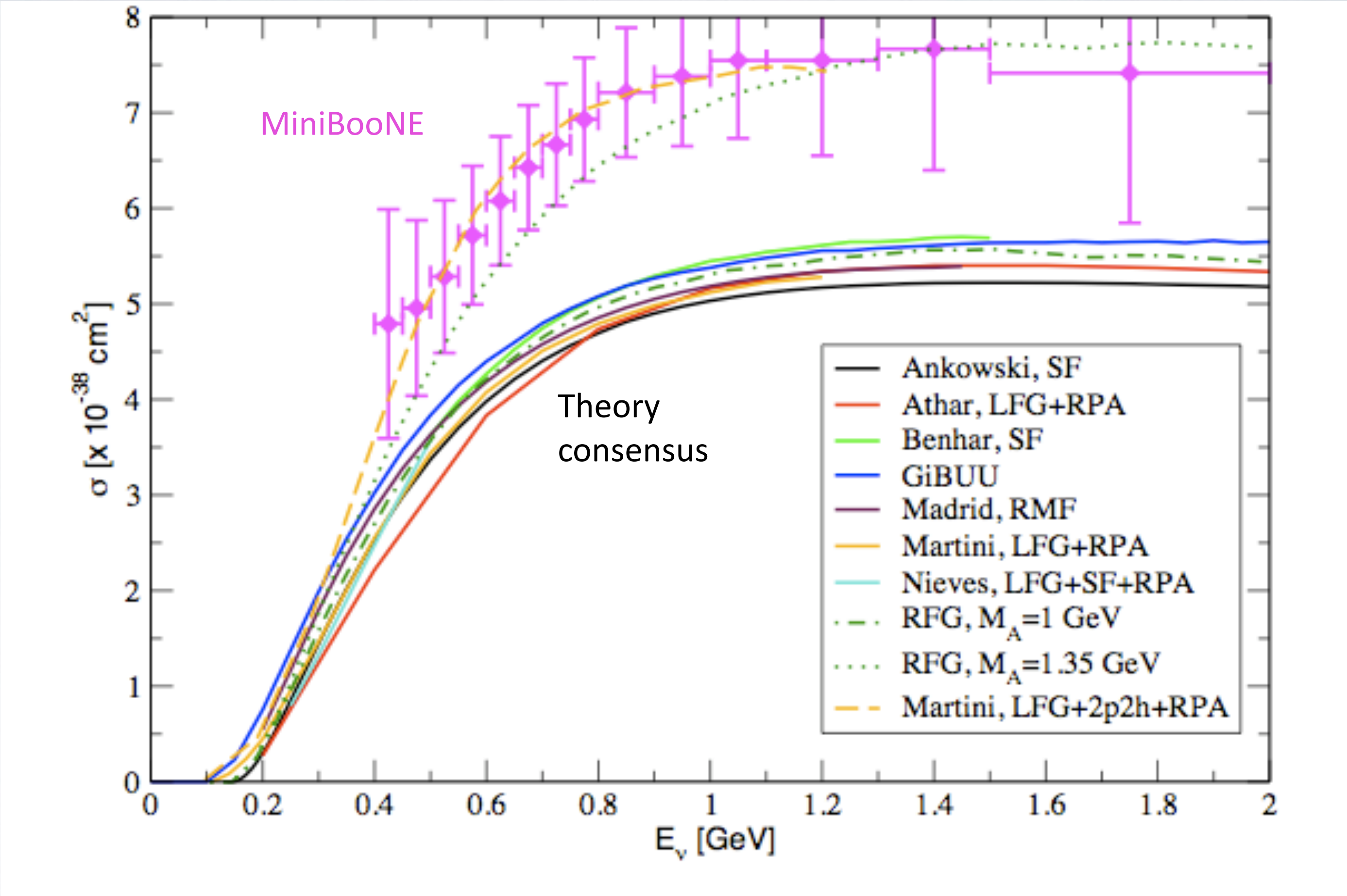
Need L - distance to detector
E - energy of neutrinos
number of neutrinos w/ different flavors
at different baselines L



MiniBoone flux

Reality: know L
mostly know flavor dependence
don't know Energy so don't know L/E
need to understand how neutrinos interact
with nuclei to reconstruct neutrino energy

Larger q: QuasiElastic Neutrino Scattering requires enhancement!



Significant Enhancement required, calculations show enhancement in Vector, Axial, and Interference Terms

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

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

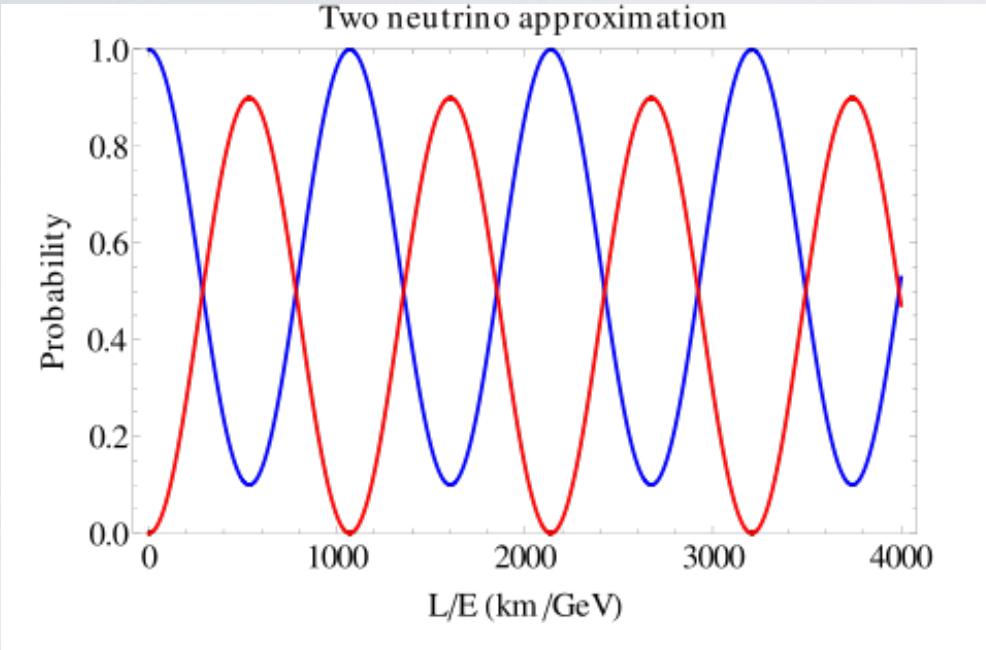
$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

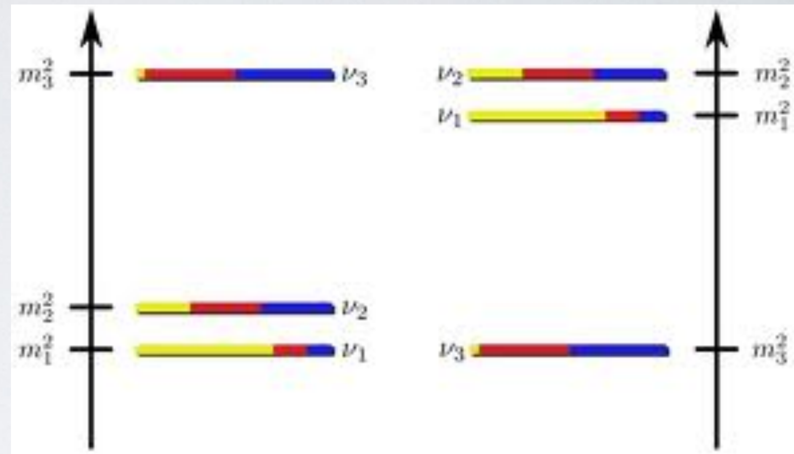
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

Mixing angles, CP violating phases, Majorana Phases
+ MSW effect from forward scattering in matter

Neutrino Oscillations: Masses and Mixing

masses, mixings from oscillations





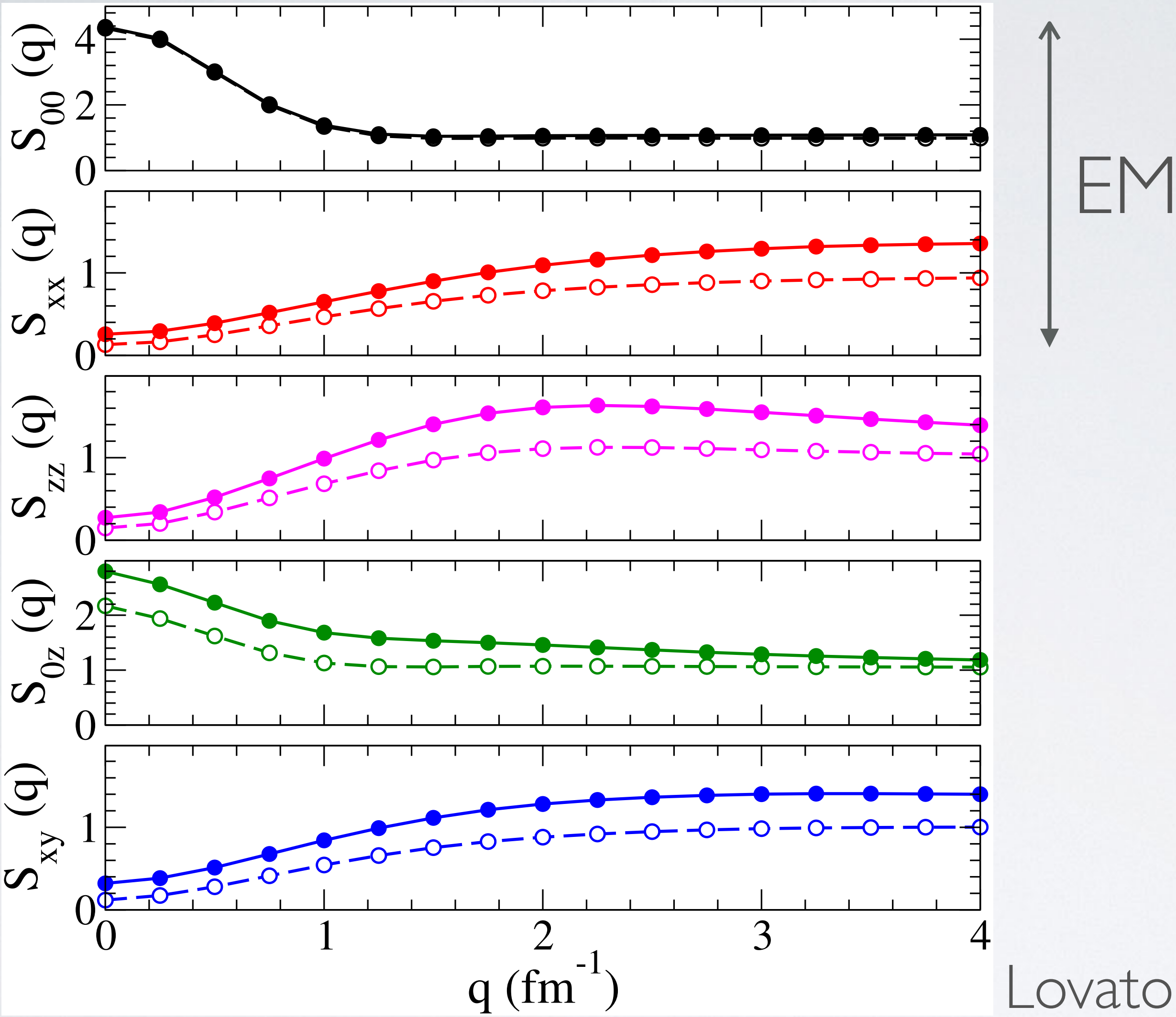
Simplified two-flavor neutrino oscillations:

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

Ratio of E/L to Δm^2 critical

Need to understand cross-section even with near and far detectors

Sum rules in ^{12}C



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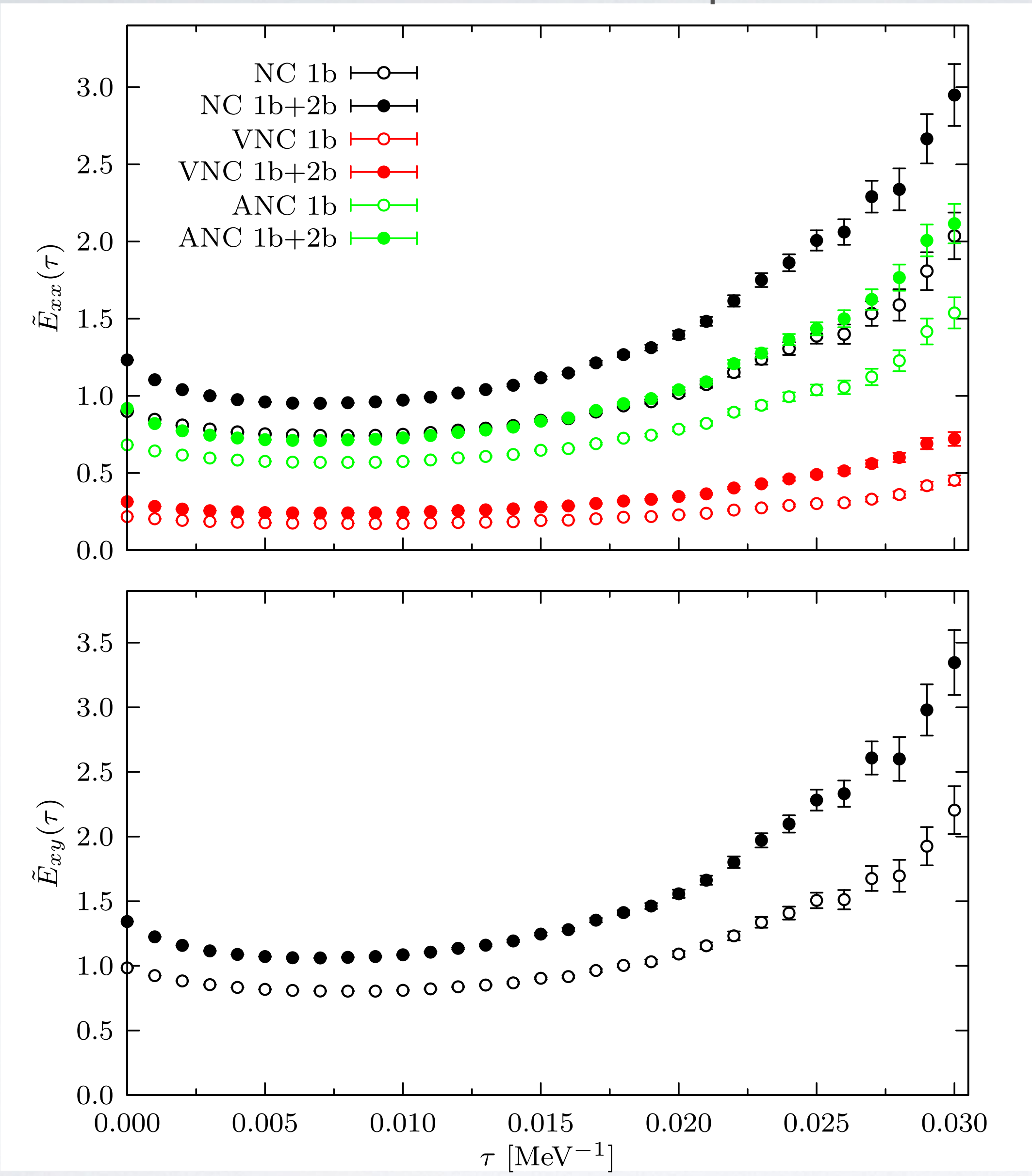
J. Carlson

Lovato, et. al PRL 2014

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

^{12}C Euclidean Response: Neutral Current



Total

Axial

Vector

V-A interference

critical for LBNF

neutrino vs. antineutrino:

CP violation

and mass hierarchy

~30% enhancement from 2N currents in all channels except Longitudinal (charge)

Lovato, et al, arXiv:1501.01981

Future Theory Efforts: Accelerator Neutrinos
Higher Energy, Larger Nuclei, more exclusive

Larger Nuclei: AFDMC (sample spins/isospins)
Coupled Cluster
Factorization Approaches
(2-nucleon level)

Higher Energy: in Factorization Approaches
Pion production, Delta, …

More Exclusive Channels: couple to
Generators (semi-classical)
at multi-nucleon level

Future: Astrophysical Neutrinos

`*Nuclear physics and neutrinos' questions:*

Neutrino decoupling - initial flux at proto-neutron star
or in neutron star mergers

Neutrino evolution - Coherent neutrino interactions
in early universe, more realistic
treatment of compact objects

Nucleosynthesis in supernovae and neutron star mergers

Open Questions

CP-violation in neutrinos

LBNF, HyperK, …

Mass hierarchy, normal or inverted?

Absolute mass scale

Neutrinoless
Double beta-decay

Majorana or Dirac masses?

Hints of *further* Beyond the Standard Model Physics?

short-baseline &
reactor experiments

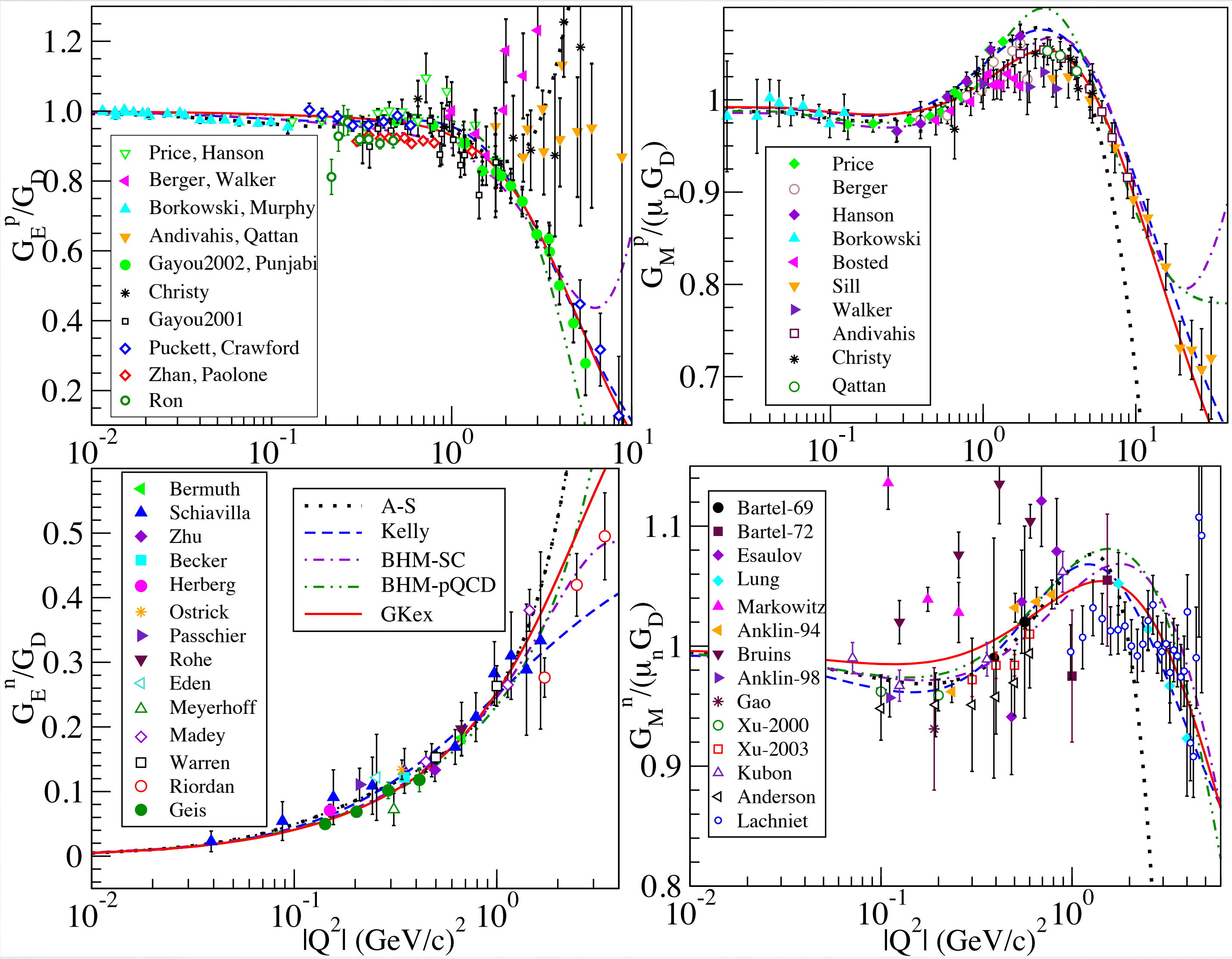
Summary

- Exciting time in Neutrino Physics
- Many prospects for discovery:
  mass hierarchy
  CP violation,
  Majorana neutrinos (lepton number violation),
  absolute mass scale
- Nuclear Physics (and computation)
  plays a key role in: astrophysics,
  supernovae, neutron stars and mergers
  and nuclear and particle physics experiments

Many thanks to:
FNAL
DOE NP
NUCLEI SciDAC-3 project (computingnuclei.org) DOE NP and ASCR
ANL devoting ~100M core-hours to this project plus staff/postdoc time
INCITE award to NUCLEI project
LANL support through LDRD-DR and LDRD-ER Projects

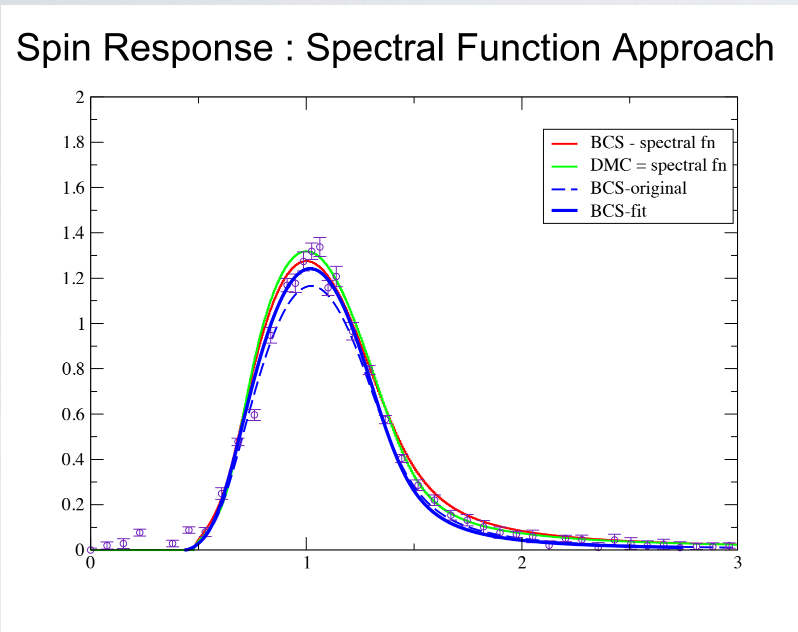
Backup Slides

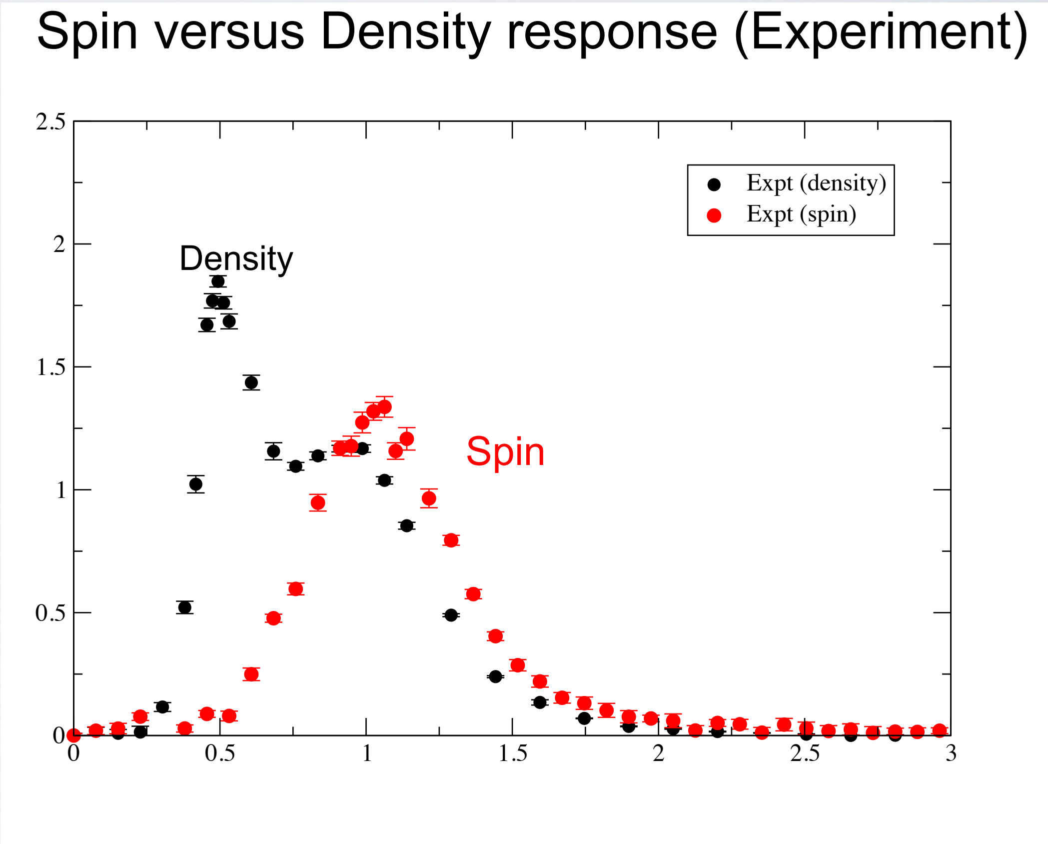
Nucleon Form Factors



Gonzalex-Jiminez, Caballero, Donnelly, Phys. Reports 2013

Cold Atoms (Fermions at Unitarity)

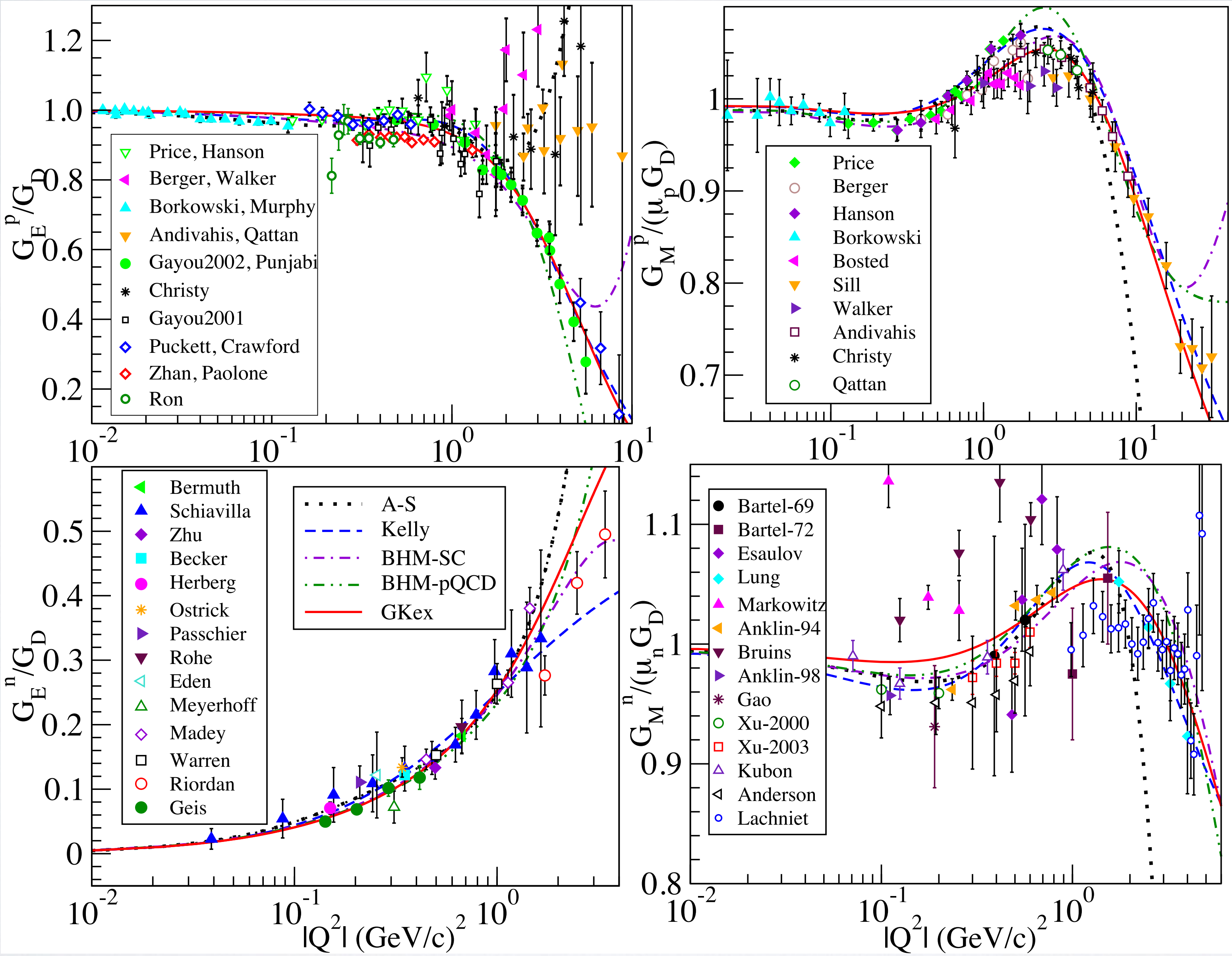




Both at q = 4.5 kF

Density and Spin Response Identical for PWIA or Spectral Function

Nucleon Form Factors



Gonzalez-Jiminez, Caballero, Donnelly, Phys. Rep. 2013

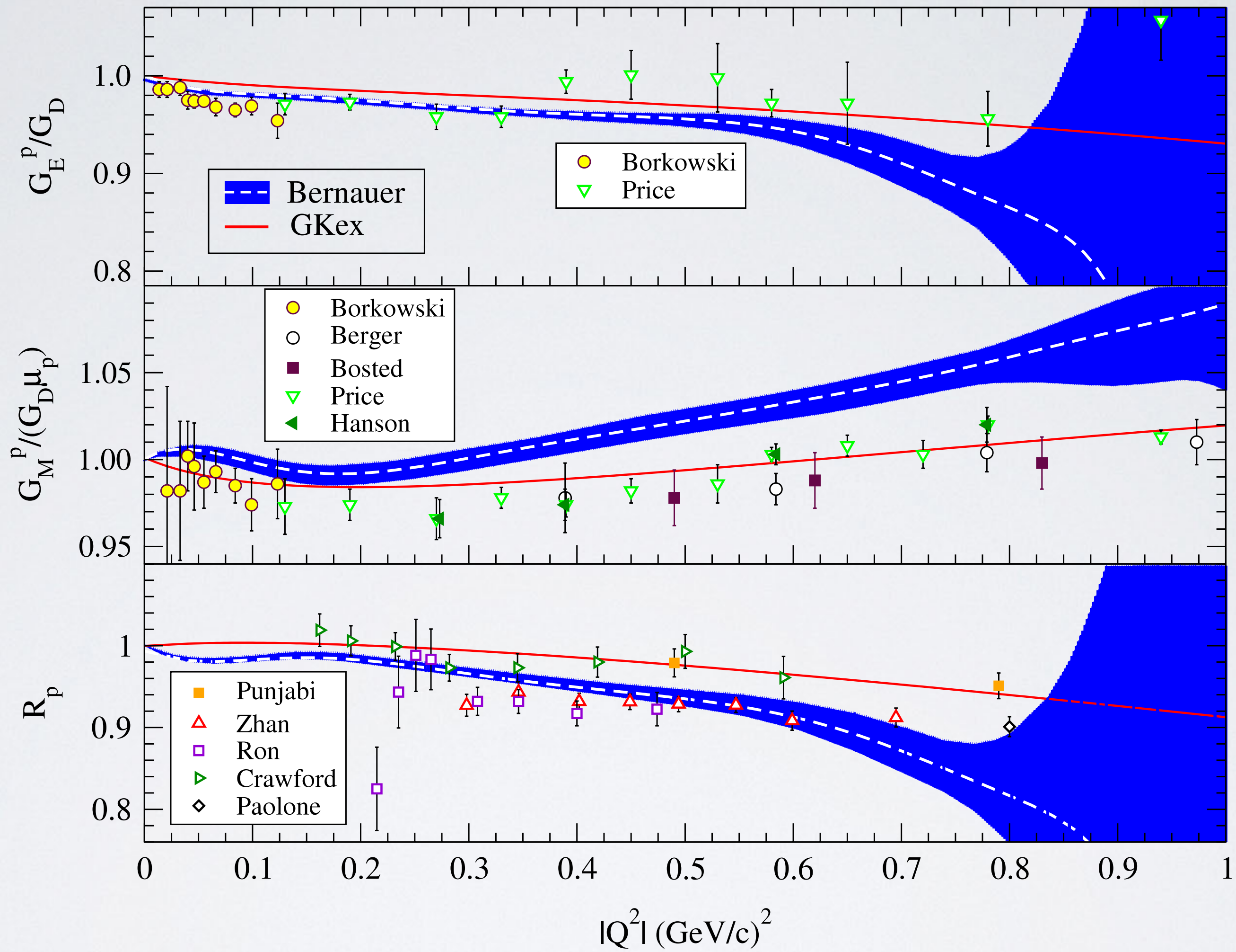
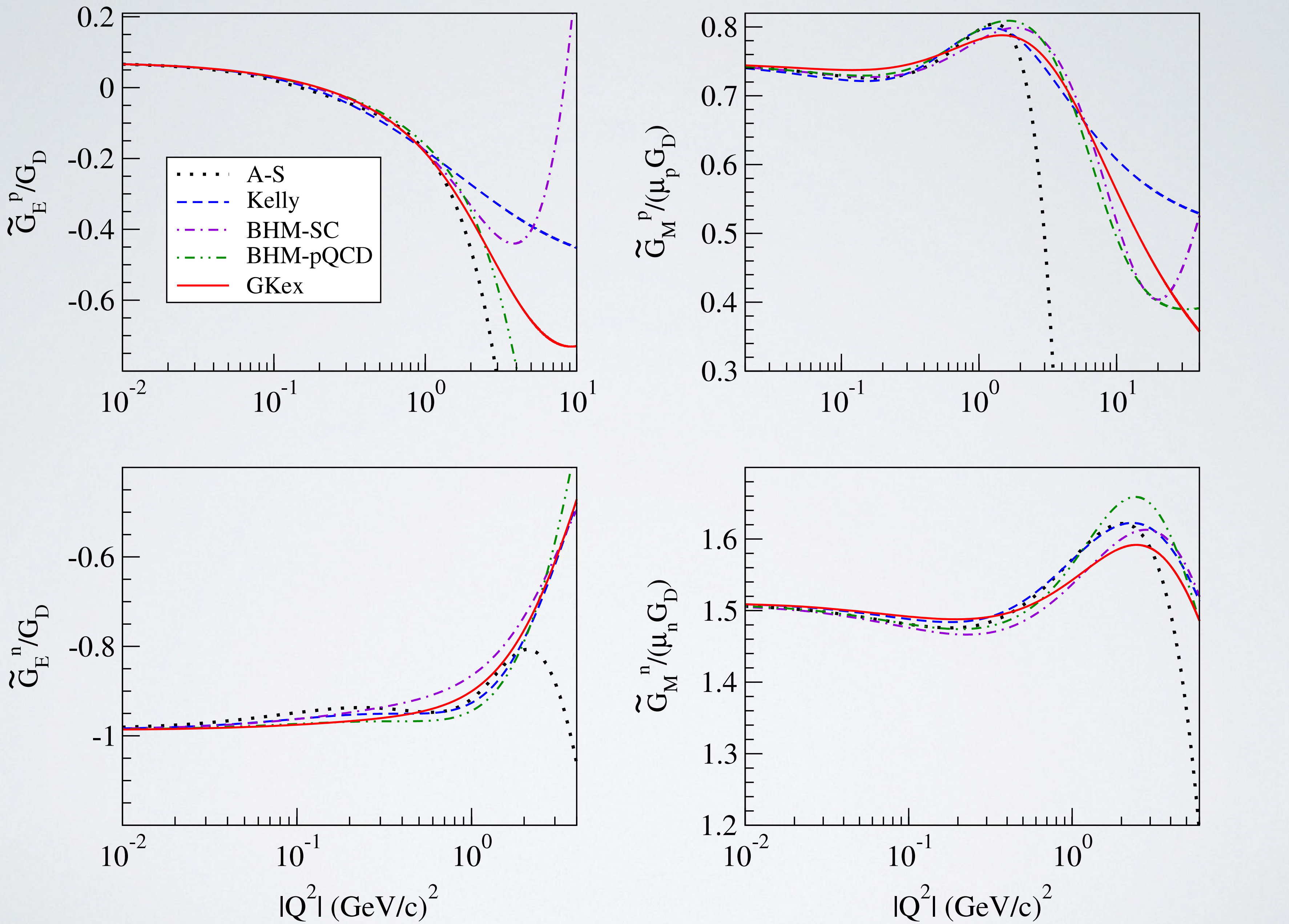


Fig. 3. (Color online) EM nucleon form factors from different experiments (see Fig. 2 for references) are compared with the GKex model and with the data of Bernauer et al. [116] (see text for details).



$\tilde{G}_E^{\ p}/G_D$
0.2
0
-0.2
-0.4
-0.6
A-S
Kelly
BHM-SC
BHM-pQCD
GKex
10^{-2}
10^{-1}
10^{0}
10^{1}
$\tilde{G}_M^{\ p}/(\mu_p G_D)$
0.8
0.7
0.6
0.5
0.4
0.3
$\tilde{G}_E^{\ n}/G_D$
-0.6
-0.8
-1
$\tilde{G}_M^{\ n}/(\mu_n G_D)$
1.6
1.5
1.4
1.3
1.2
$|Q^2|$ (GeV/c)^2
$|Q^2|$ (GeV/c)^2