Neutrino-Nucleus Interactions

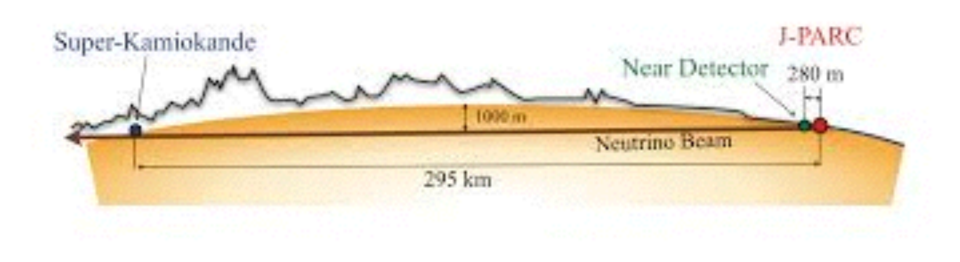
J. Carlson - LANL

- Different energy and momentum regimes
  and different processes (beta decay, …)
- `Realistic` model ingredients
- A=2 (deuteron)
- Light Nuclei (A ≲ 12)
- Medium/Heavy Nuclei (Ar, Pb, …)
- Relations to matter
- Outlook

see Formaggio and Zeller, RMP, 2013
Scholberg, ARNPS, 2012

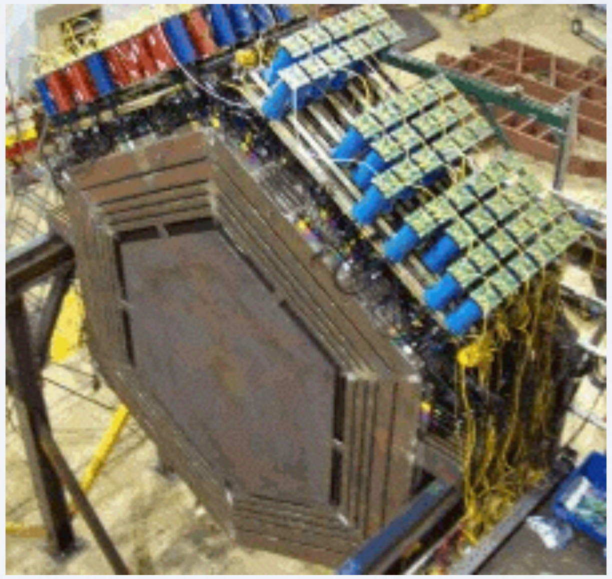
Accelerator Neutrinos

T2K

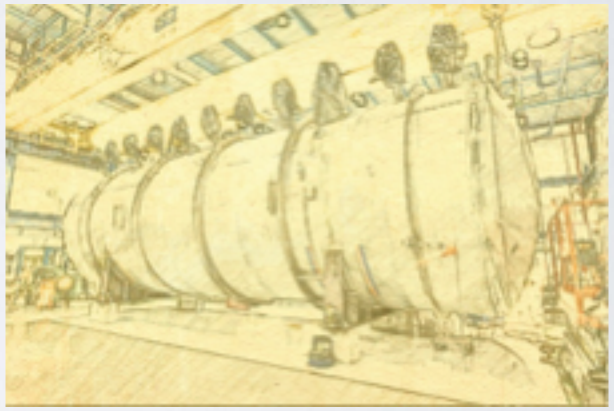


MINOS

SuperK

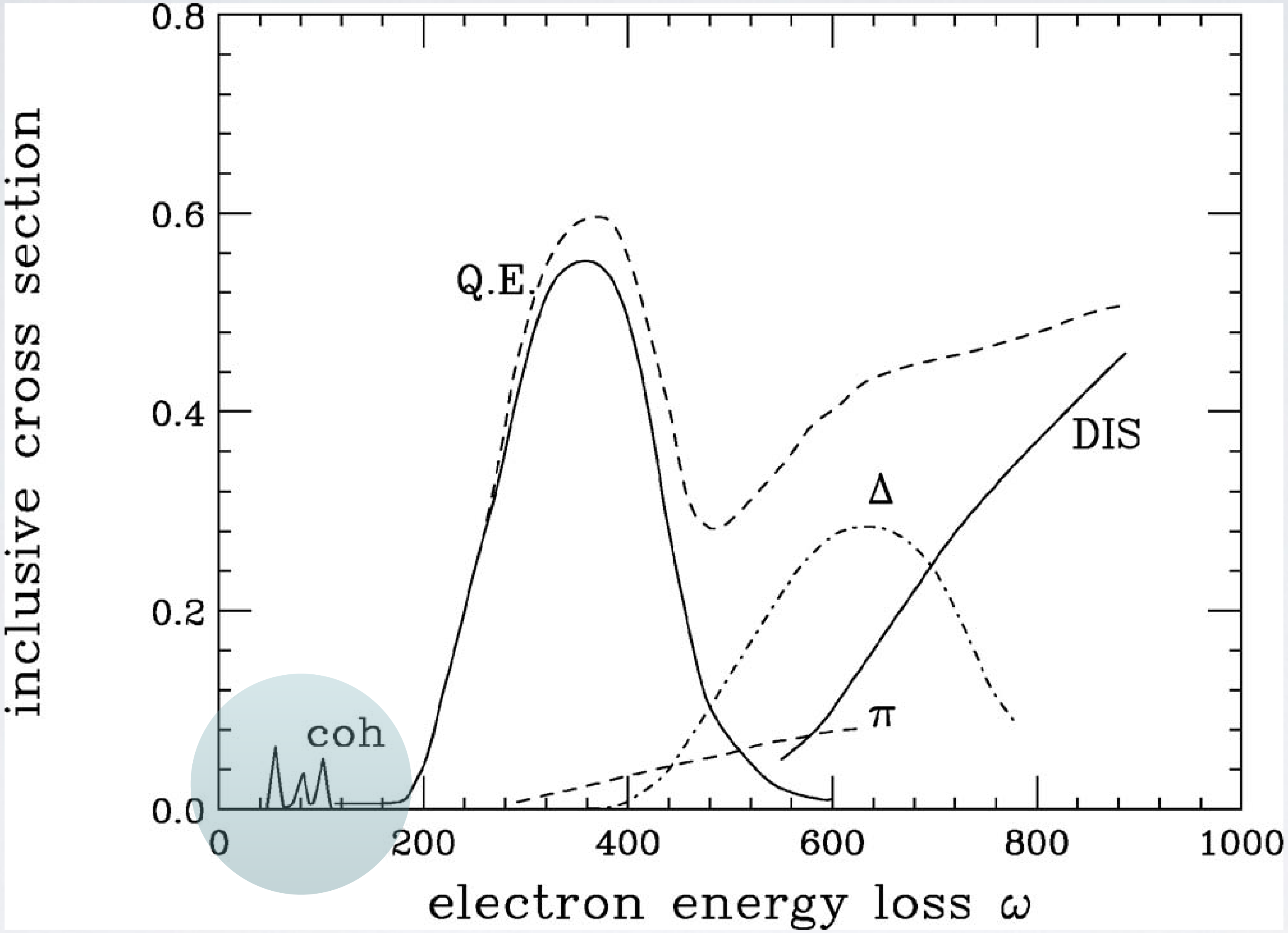


MINERva



MicroBooNE

Accelerator Electron/Neutrino Scattering

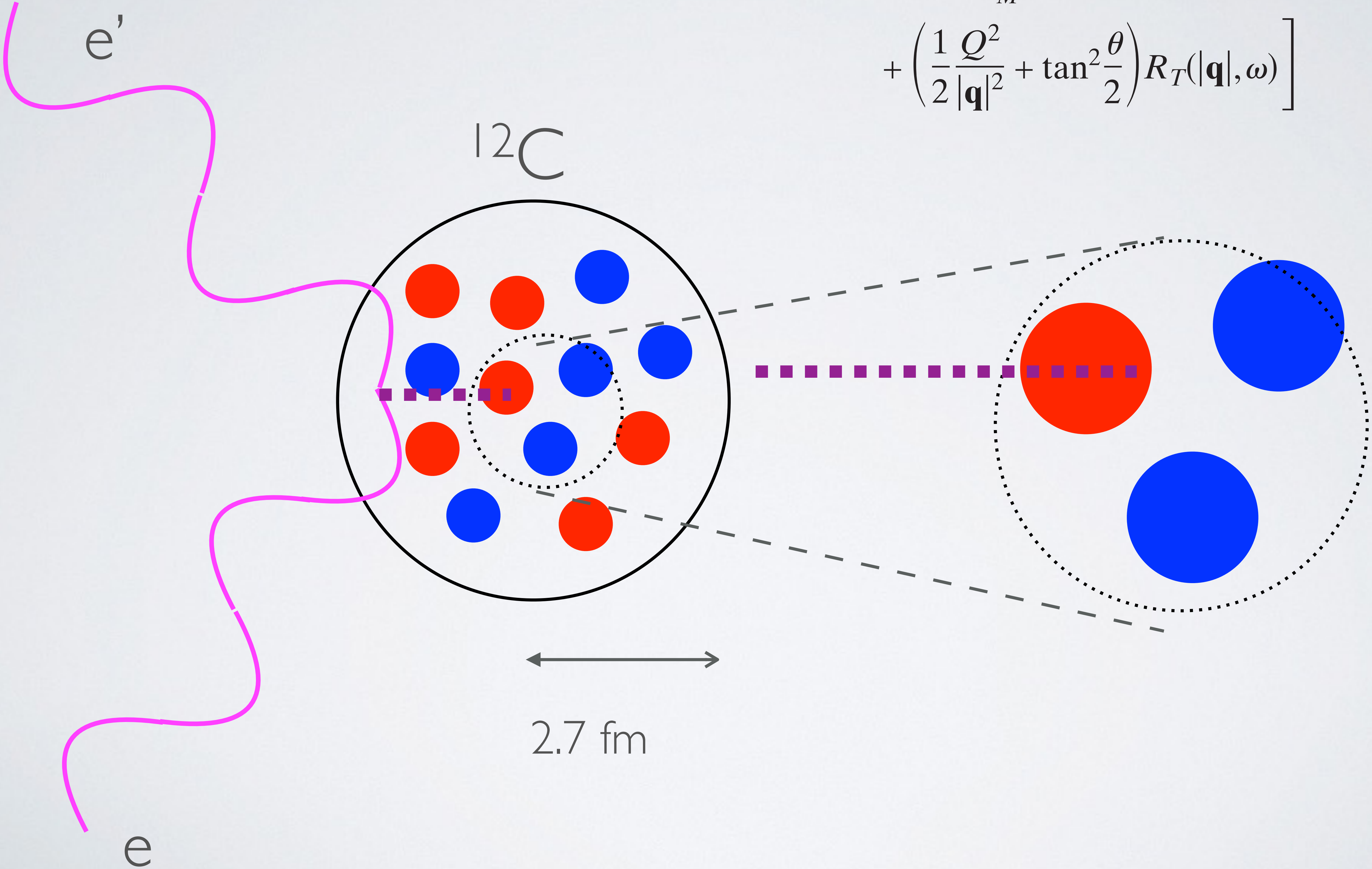


Benhar, Day, Sick, RMP 2008

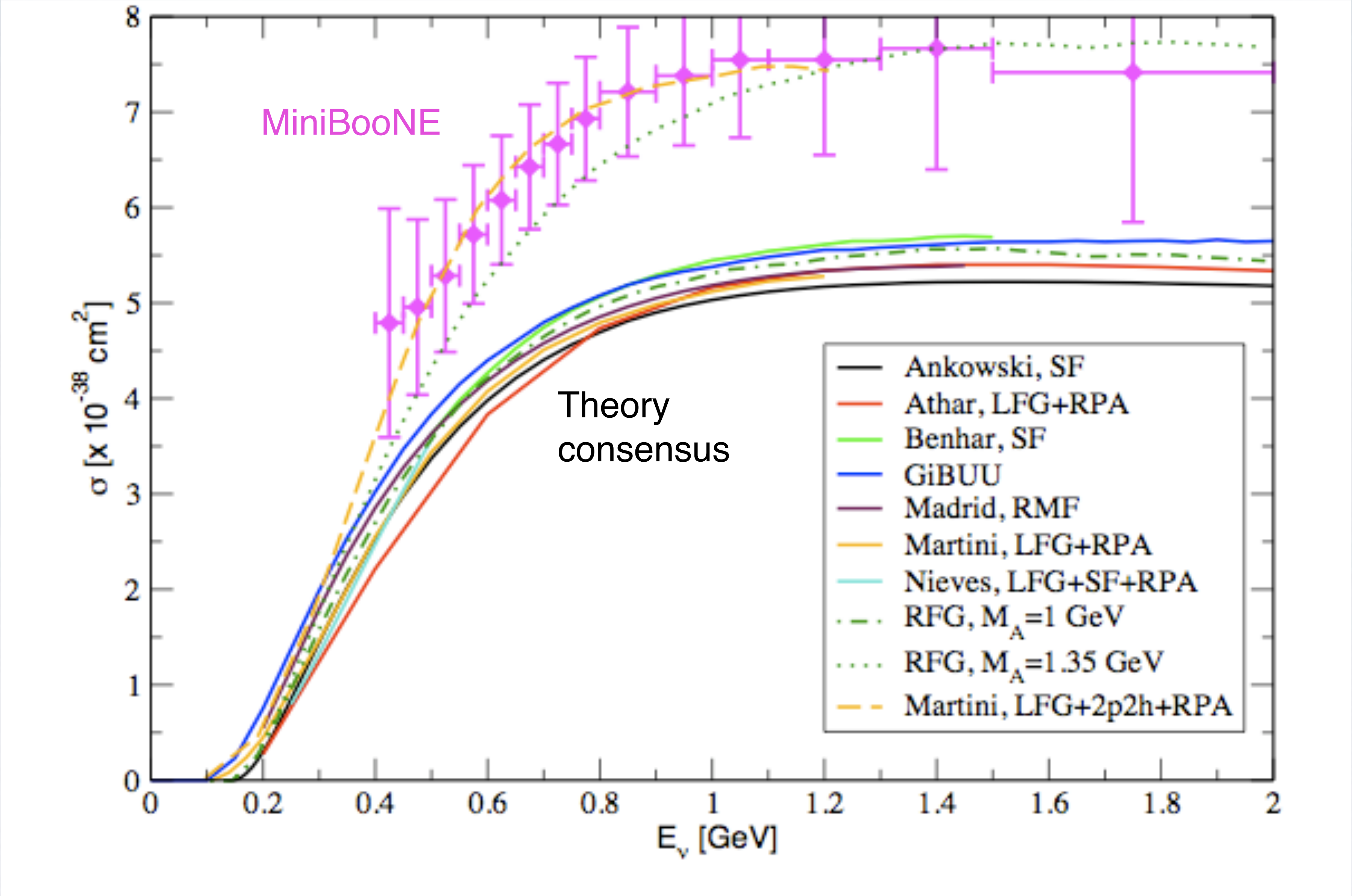
Inclusive electron scattering at larger q

measure electron kinematics only

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



Simple Models of QuasiElastic Neutrino Scattering



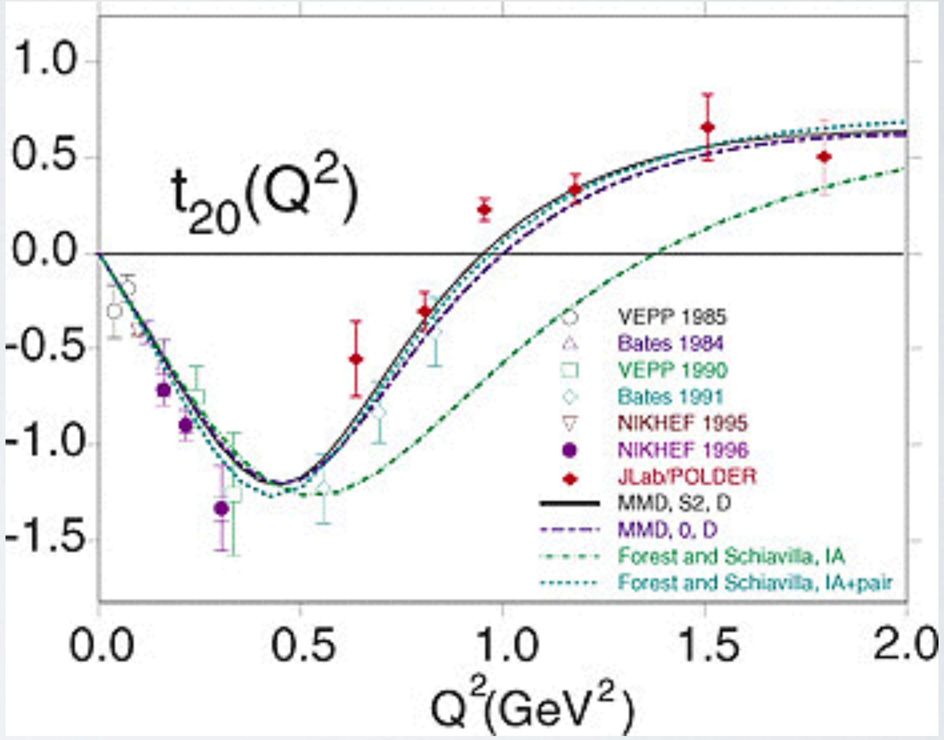
Simplest models fail at 30-40% level (too small)
requires two-nucleon currents and correlations

Nuclear Interactions and Currents

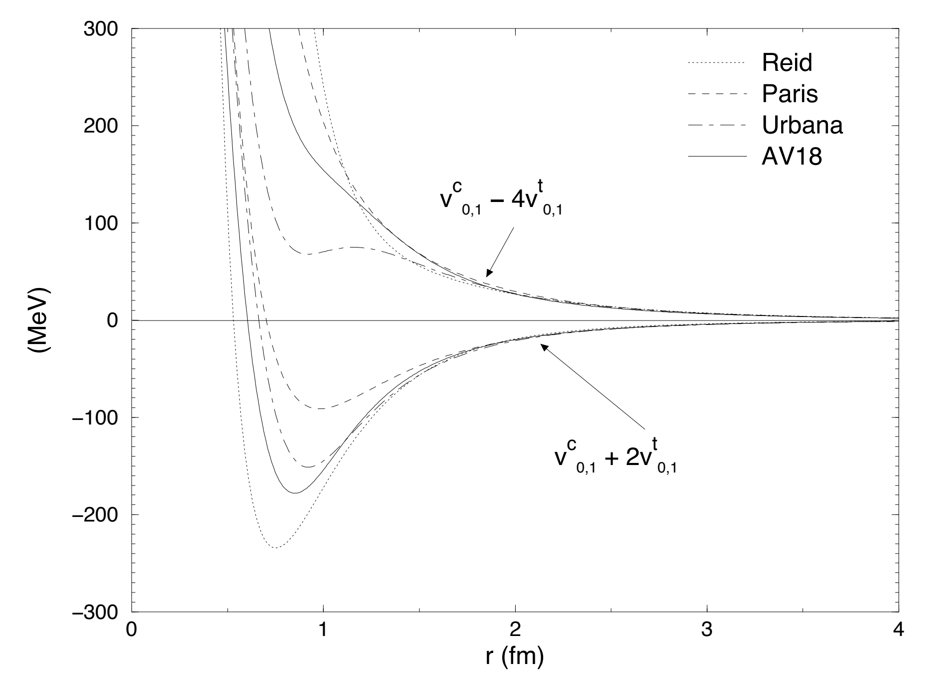
Non-relativistic nucleons w/ 2, 3-body interactions, currents

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

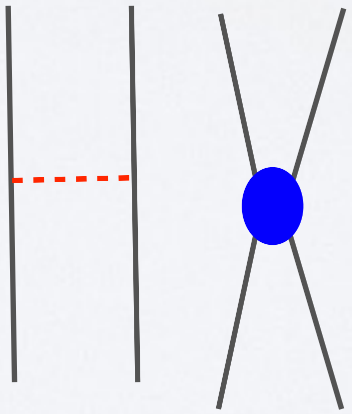
$$\mathbf{J} = \sum_i \mathbf{j}_{1;i} + \sum_{i<j} \mathbf{j_{2;ij}} + \ldots$$

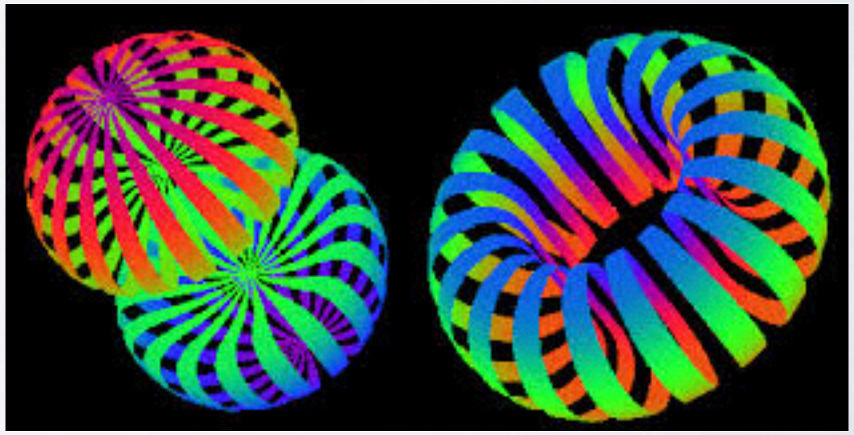


t20 experiment Jlab R. Holt



Deuteron Potential Models with Different Spin Orientations

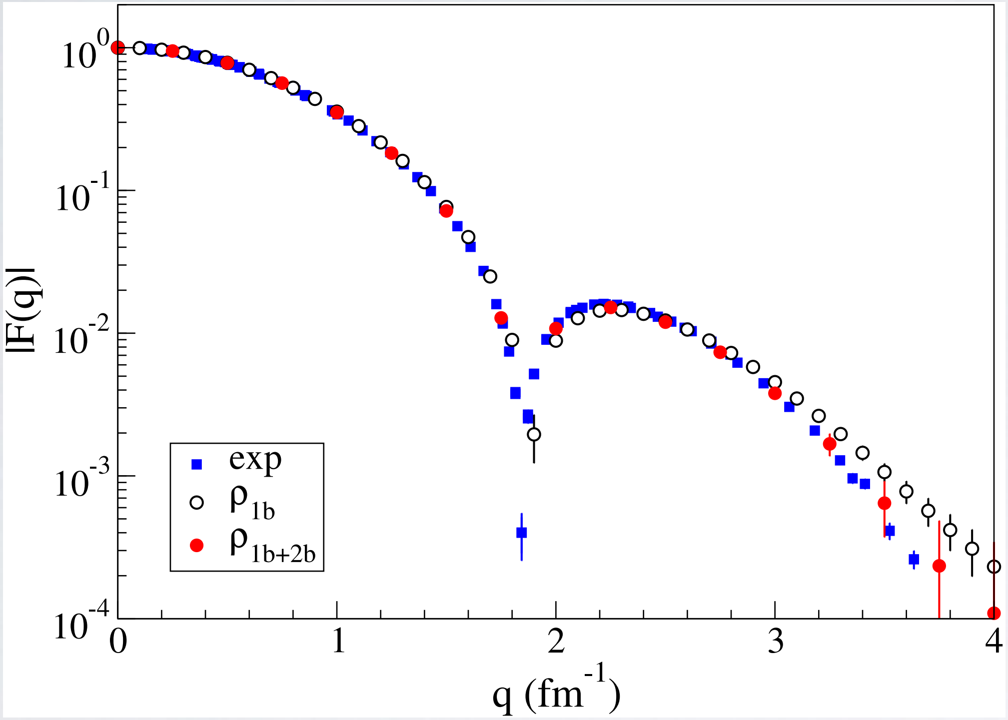


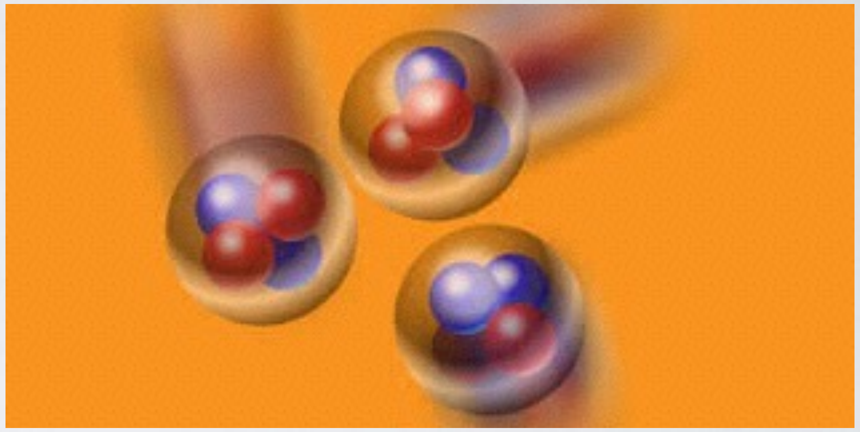


Forrest, et al, PRC 1996

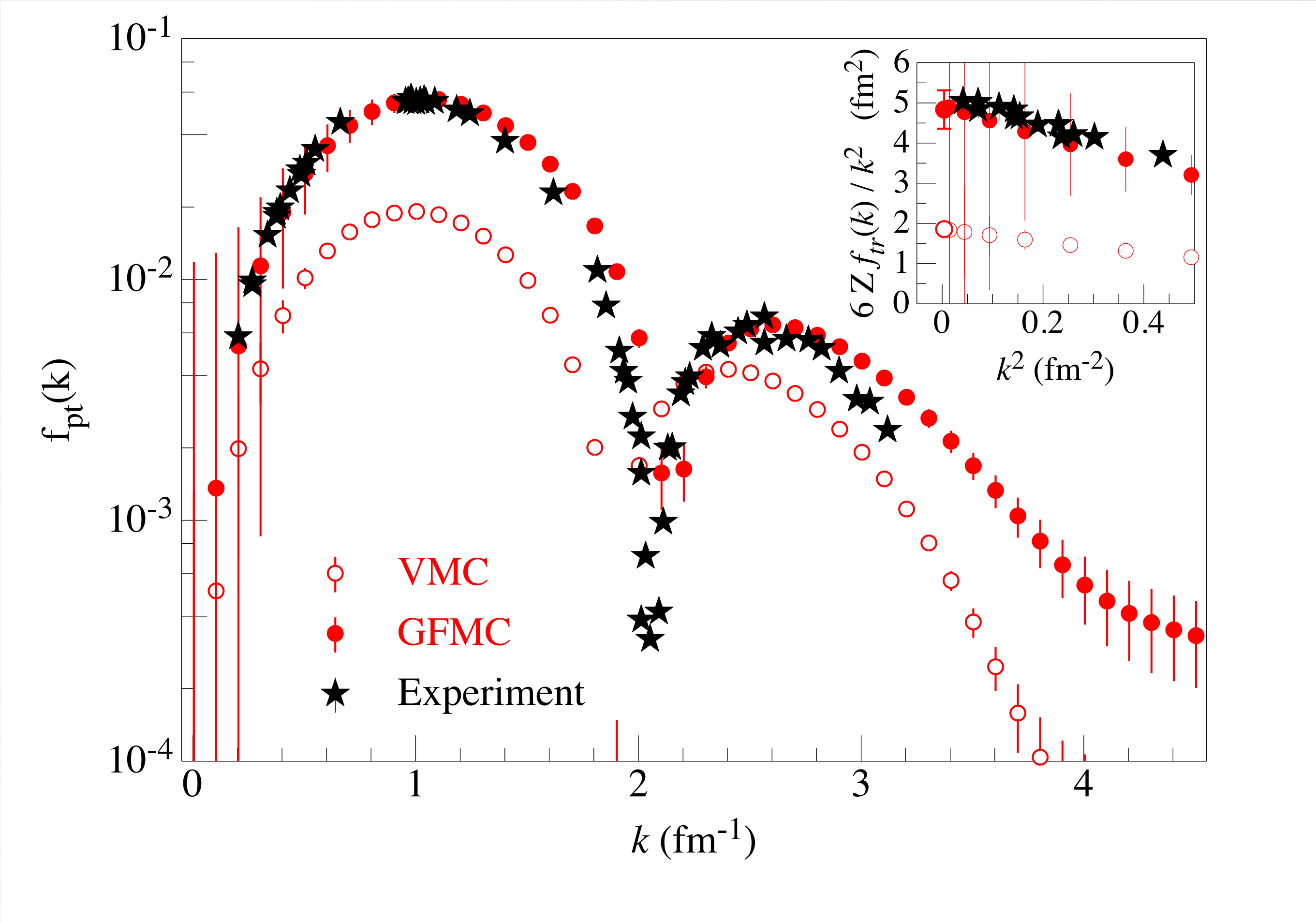
Many measurements in EM sector
Currents and elastic/transition form factors

^{12}C elastic form factor





Hoyle state transition form factor

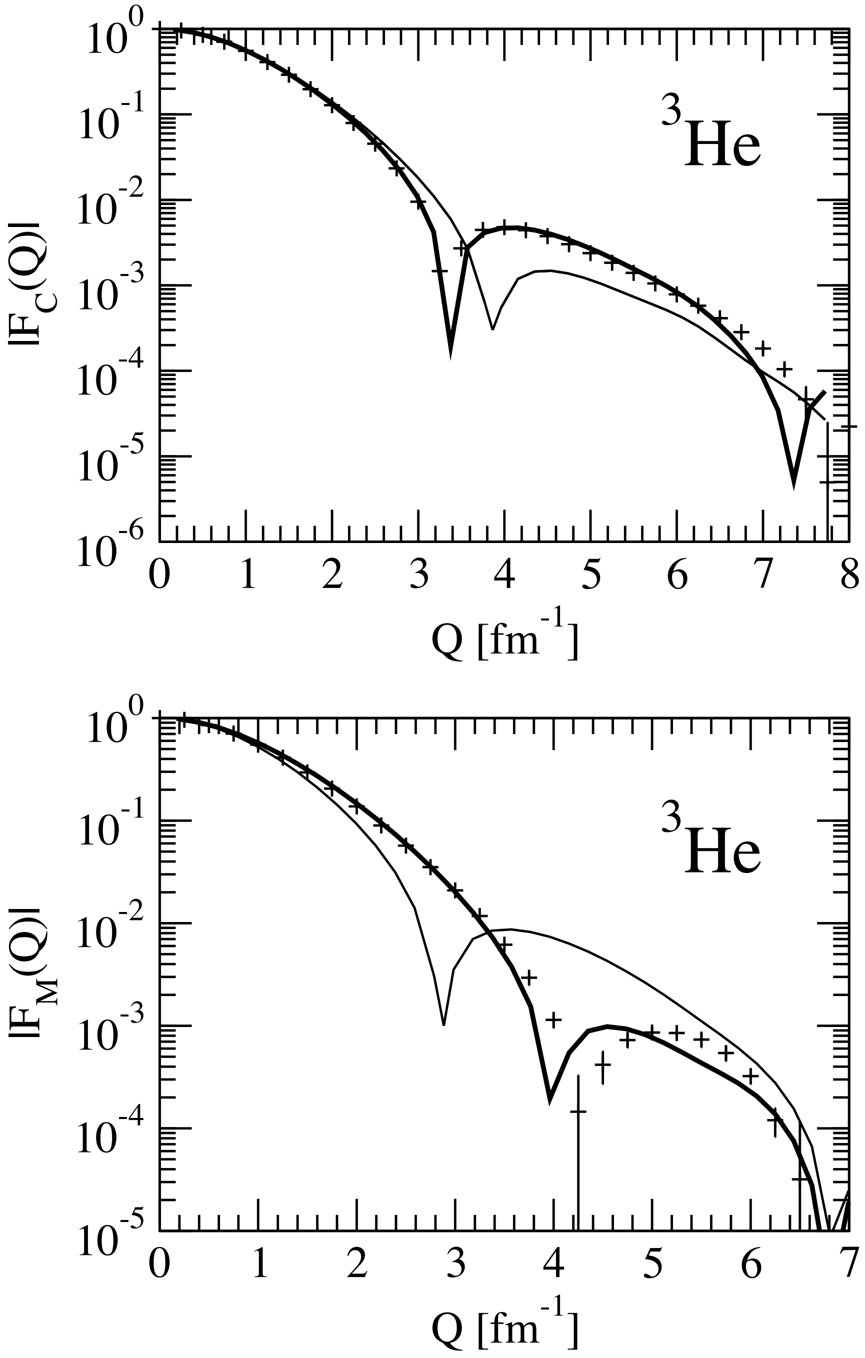


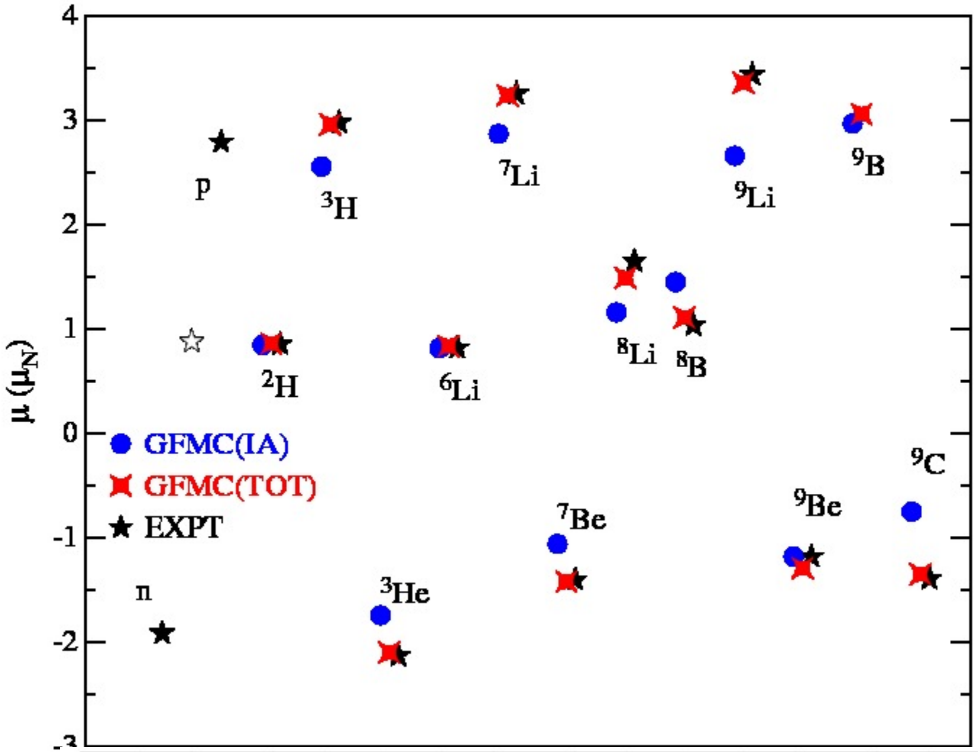
2 Nucleon charge operators
(relativistic corrections)
are small

NUCLEI
Nuclear Computational Low-Energy Initiative

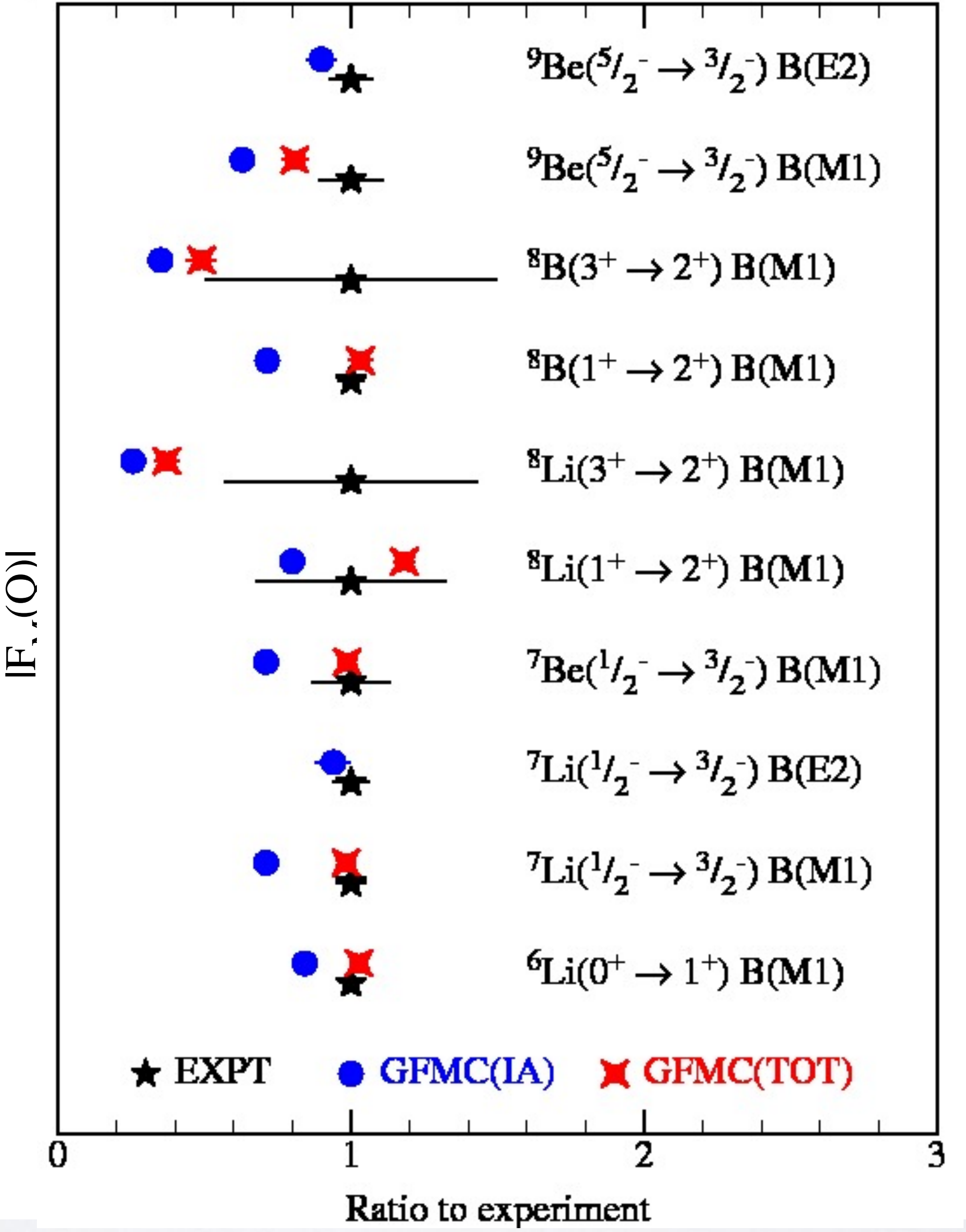
2-Nucleon Currents

Form Factors





Magnetic Moments



EM Transitions

NUCLEI
Nuclear Computational Low-Energy Initiative

Wiringa, Pastore, Schiavilla, et al

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

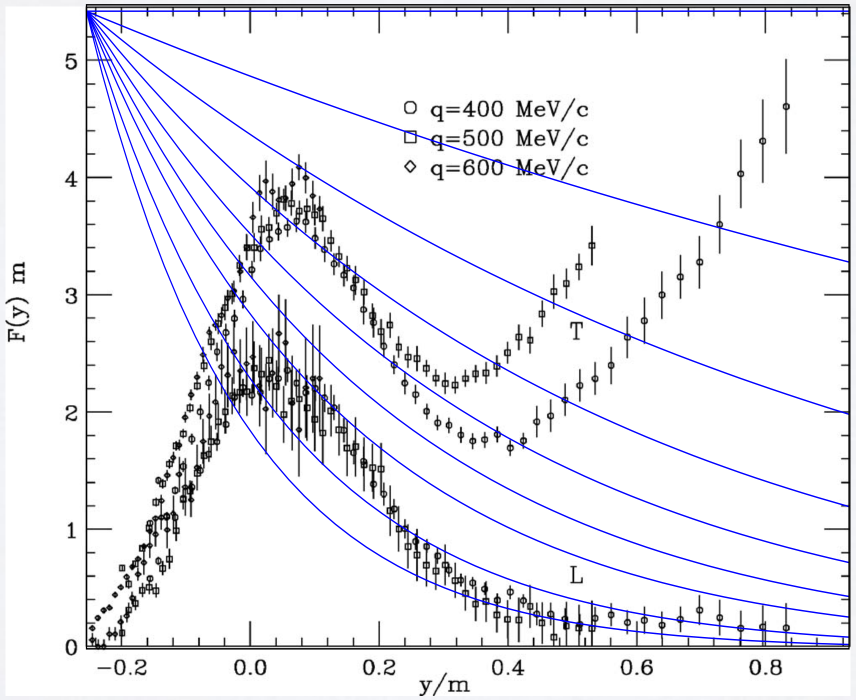
Explicit Final States $\quad \sigma \propto \left|\langle f \;| \mathbf{J}(\mathbf{q}) |\; i \rangle\right|^2$

Sum Rules: ground-state observable

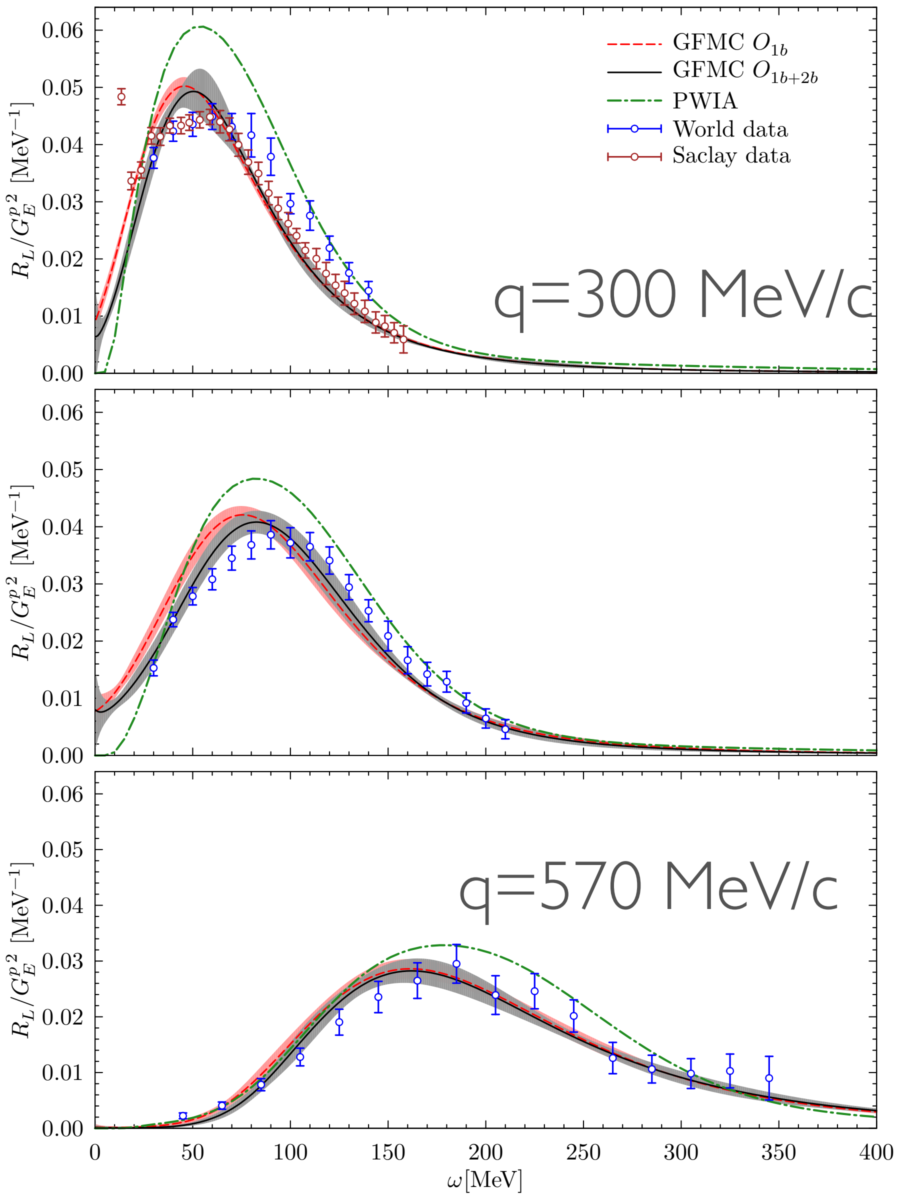
$$S(q) \;=\; \int d\omega\ R(q,\omega) = \langle 0 | O^\dagger(q)\ O(q) | 0 \rangle$$

Imaginary Time Correlations(Euclidean Response)

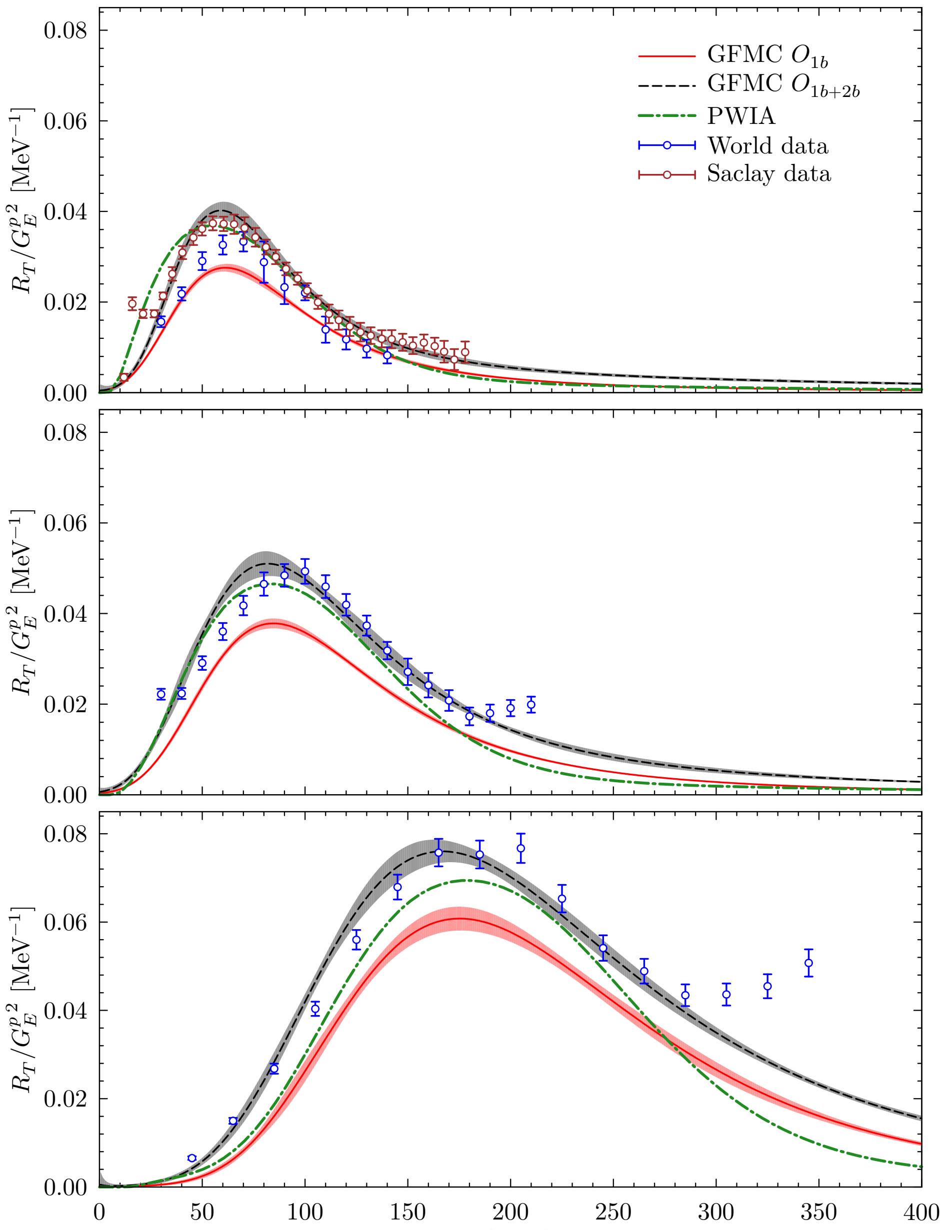
$$\tilde{R}(q,\tau) \;=\; \langle 0|\ \mathbf{j}^\dagger\ \exp[-(\mathbf{H}-\mathbf{E_0}-\mathbf{q^2}/(\mathbf{2m}))\tau]\ \ \mathbf{j}\ |\mathbf{0}\rangle >$$



Quasi-elastic electron scattering on ^{12}C



Longitudinal



Transverse

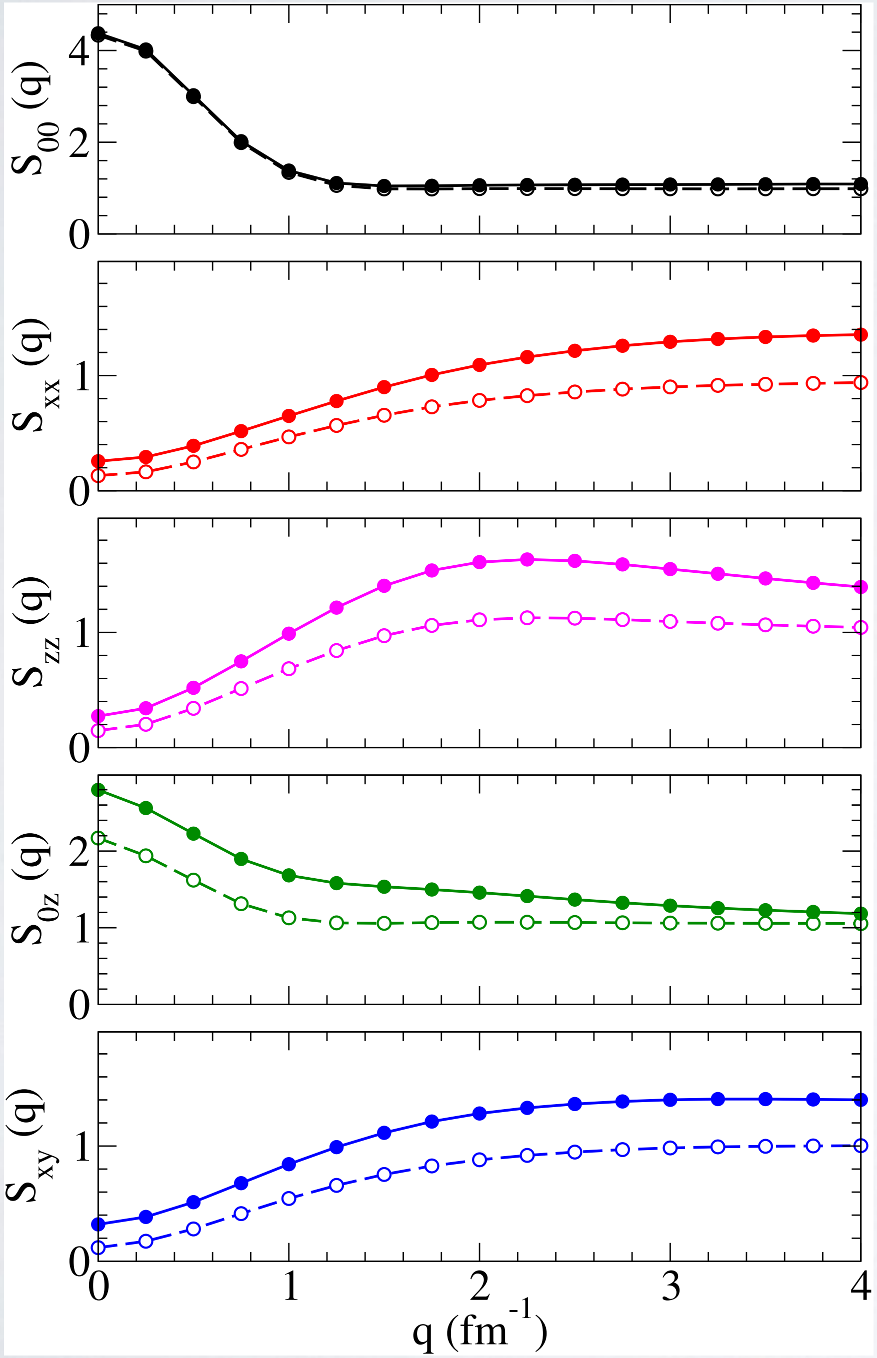
Lovato, et al, PRL 2016

Enhancement in Transverse channel

Explicit 0+, 2+, 4+ states important at q=300 MeV/c

Neutral Current Sum Rules in ^{12}C

Sum Rules



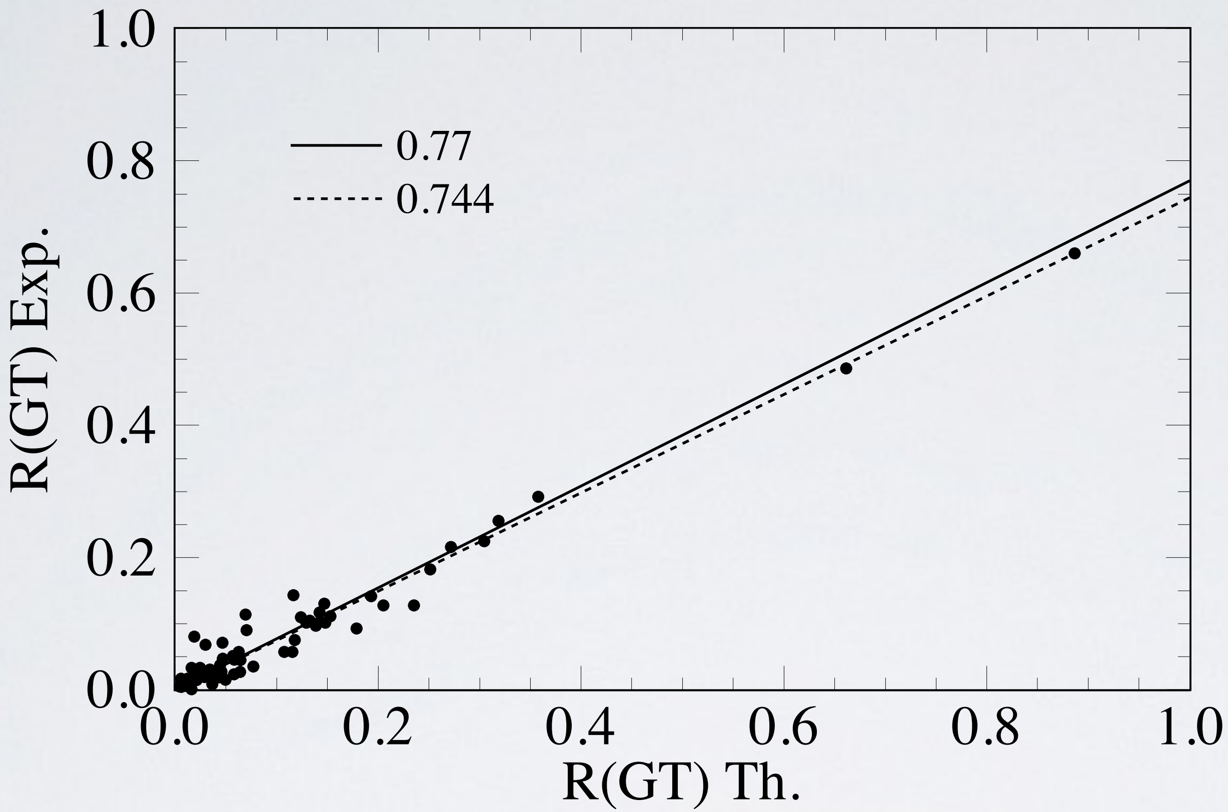
cross-section depends upon
5 response fns

all except longitudinal response enhanced
including axial-vector interference

sum rules - ground state expectation value

enhanced even at very low q, but strength
inaccessible to low energy neutrinos

Low Momentum Transfer: GT Beta Decay



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

Rate reduction by 30-40%

Martinez-Pinedo and Poves, PRC 1996

	Simple	1-Body current	1+2 current	Exp$^{\odot}$
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)

Astrophysical Energy Neutrinos

- Energies up to 50 - 100 MeV

- Explicit final states and inclusive scattering measurable

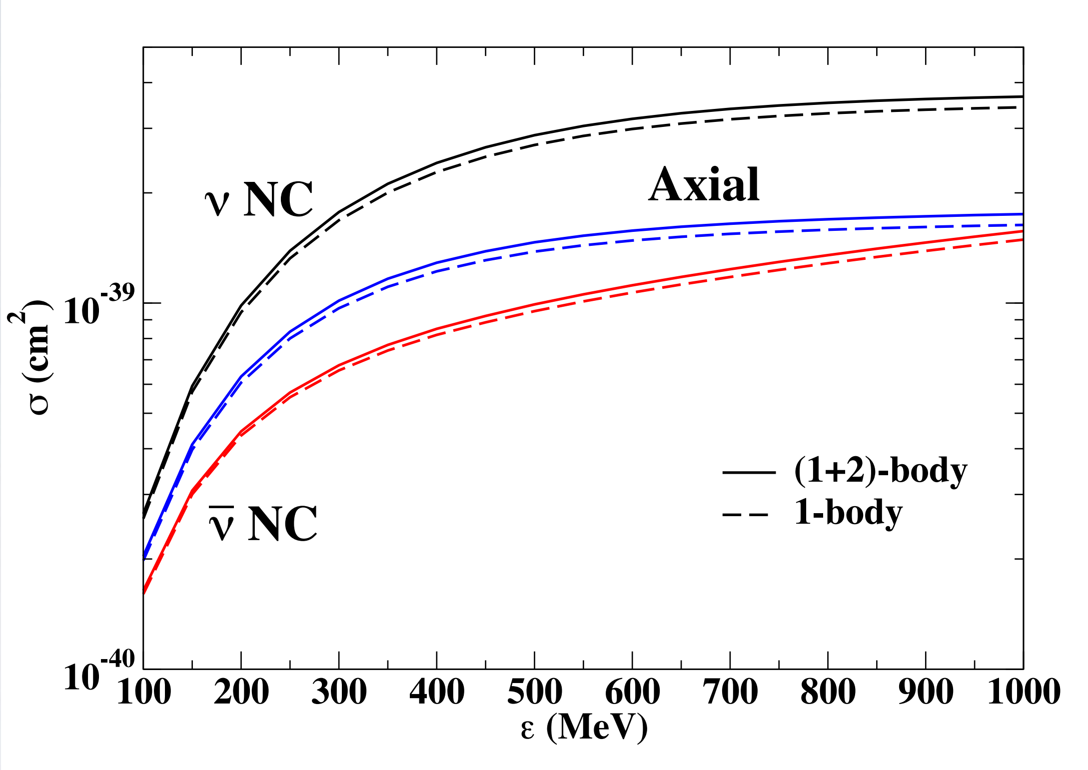
- Nucleon couplings pretty well known

- What are the roles of nuclear structure, two nucleon correlations and currents ?

- Momentum transfer much less than QE, but greater than beta decay.

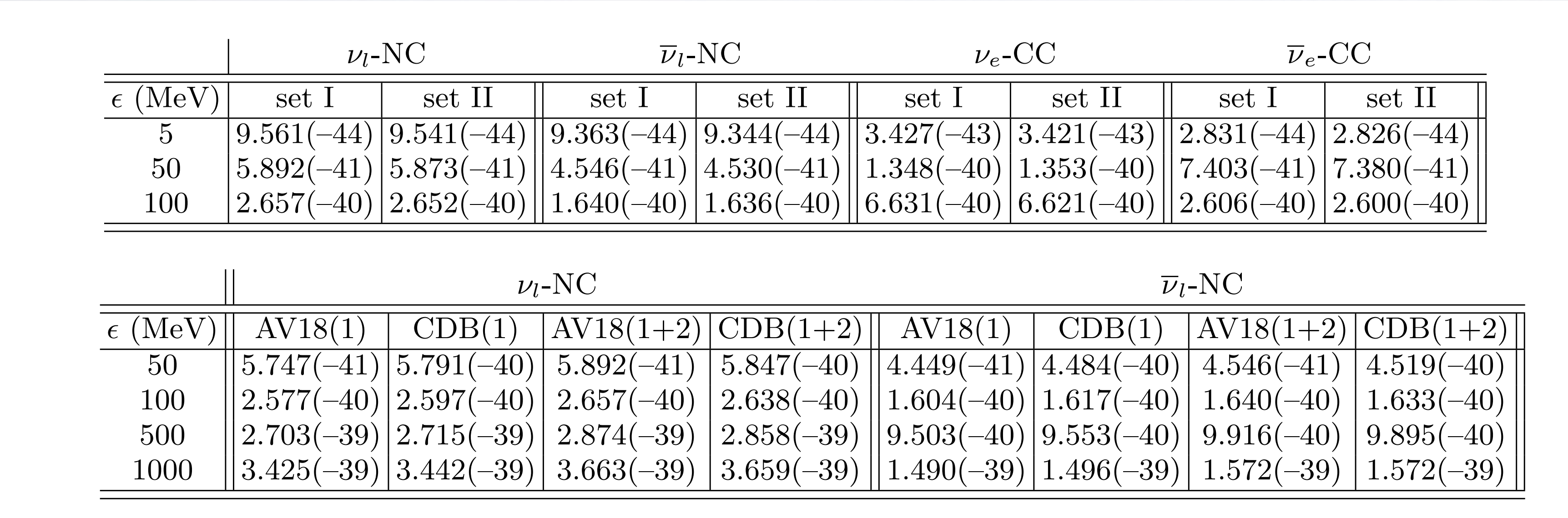
Neutrino-Deuteron Scattering

A=2



Nakamura, et al, 2001
Shen, et al., PRC 2012

currents fit to tritium beta decay
small effects from 2-nucleon currents
small (few %) model dependence



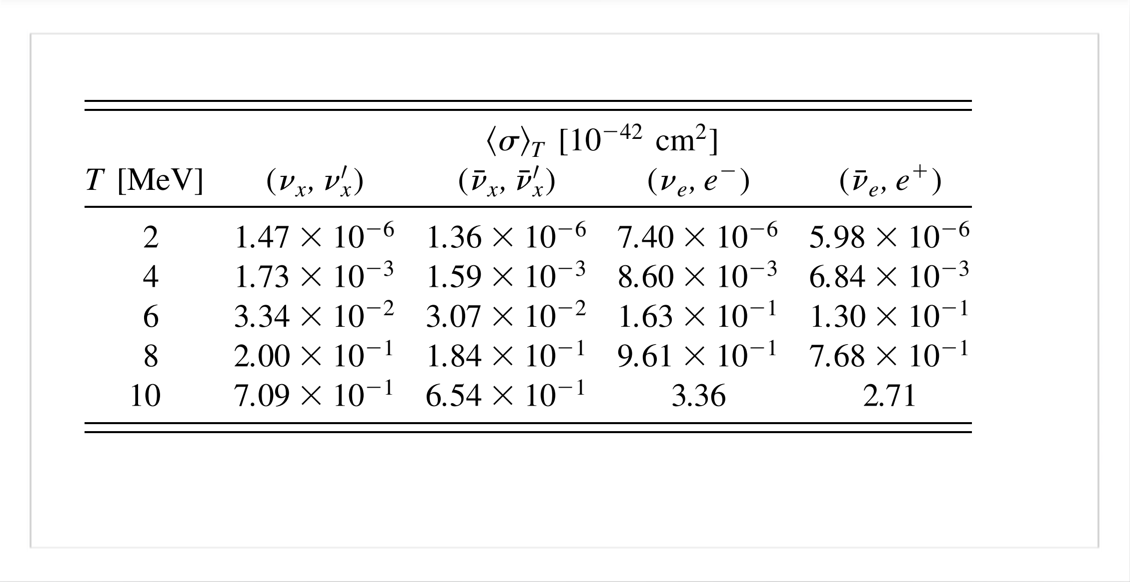
	ν_l-NC		$\overline{\nu}_l$-NC		ν_e-CC		$\overline{\nu}_e$-CC	
ϵ (MeV)	set I	set II	set I	set II	set I	set II	set I	set II
5	9.561(−44)	9.541(−44)	9.363(−44)	9.344(−44)	3.427(−43)	3.421(−43)	2.831(−44)	2.826(−44)
50	5.892(−41)	5.873(−41)	4.546(−41)	4.530(−41)	1.348(−40)	1.353(−40)	7.403(−41)	7.380(−41)
100	2.657(−40)	2.652(−40)	1.640(−40)	1.636(−40)	6.631(−40)	6.621(−40)	2.606(−40)	2.600(−40)

	ν_l-NC				$\overline{\nu}_l$-NC			
ϵ (MeV)	AV18(1)	CDB(1)	AV18(1+2)	CDB(1+2)	AV18(1)	CDB(1)	AV18(1+2)	CDB(1+2)
50	5.747(−41)	5.791(−40)	5.892(−41)	5.847(−40)	4.449(−41)	4.484(−40)	4.546(−41)	4.519(−40)
100	2.577(−40)	2.597(−40)	2.657(−40)	2.638(−40)	1.604(−40)	1.617(−40)	1.640(−40)	1.633(−40)
500	2.703(−39)	2.715(−39)	2.874(−39)	2.858(−39)	9.503(−40)	9.553(−40)	9.916(−40)	9.895(−40)
1000	3.425(−39)	3.442(−39)	3.663(−39)	3.659(−39)	1.490(−39)	1.496(−39)	1.572(−39)	1.572(−39)

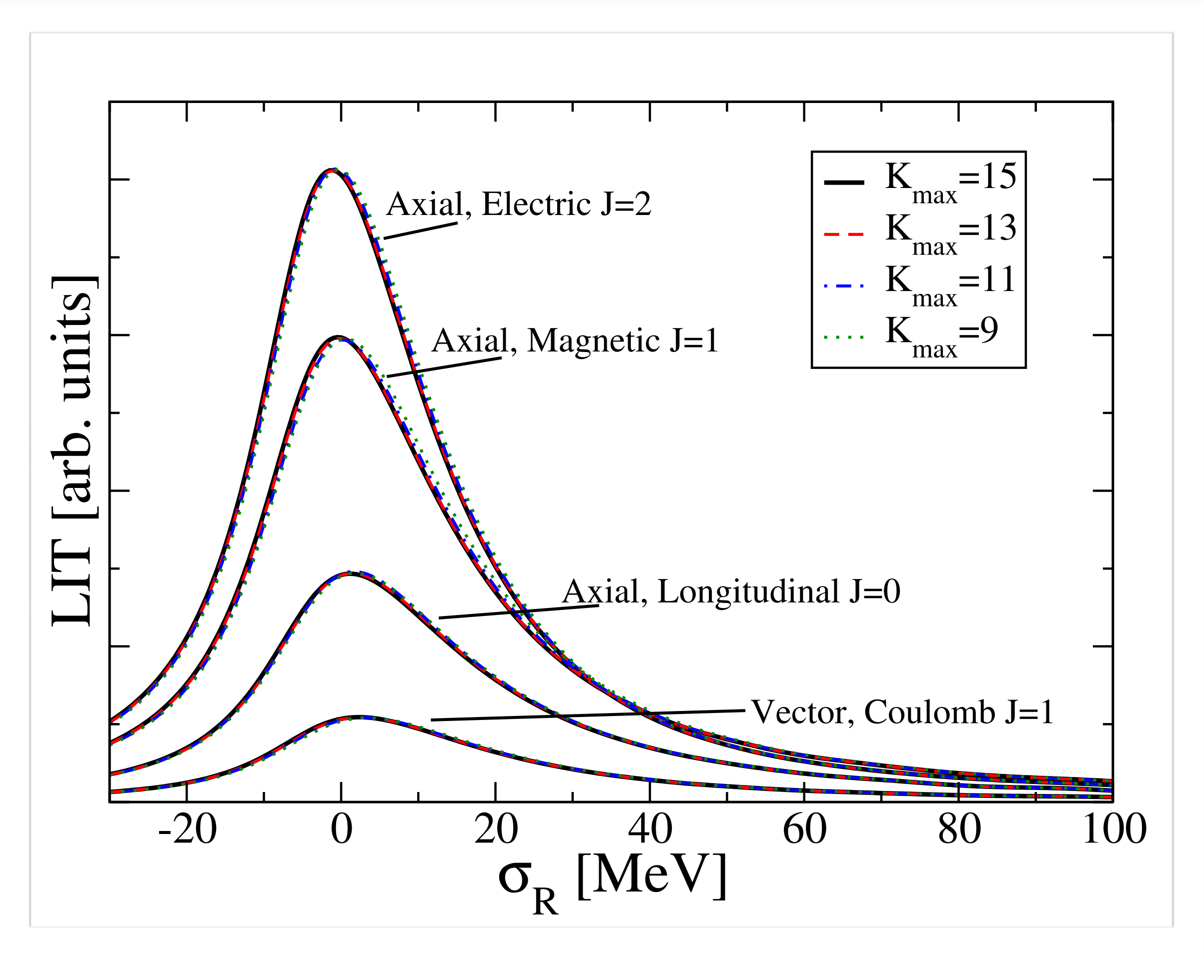
typically ~20%
accuracy from
reactor experiments

Formaggio and Zeller

Neutrino-^{4}He Scattering



	$\langle\sigma\rangle_T$ [10^{-42} cm^2]			
T [MeV]	(ν_x, ν'_x)	$(\bar{\nu}_x, \bar{\nu}'_x)$	(ν_e, e^-)	$(\bar{\nu}_e, e^+)$
2	1.47×10^{-6}	1.36×10^{-6}	7.40×10^{-6}	5.98×10^{-6}
4	1.73×10^{-3}	1.59×10^{-3}	8.60×10^{-3}	6.84×10^{-3}
6	3.34×10^{-2}	3.07×10^{-2}	1.63×10^{-1}	1.30×10^{-1}
8	2.00×10^{-1}	1.84×10^{-1}	9.61×10^{-1}	7.68×10^{-1}
10	7.09×10^{-1}	6.54×10^{-1}	3.36	2.71



Thermal averaged cross sections
Few % impact of two-nucleon currents

convergence in each partial wave

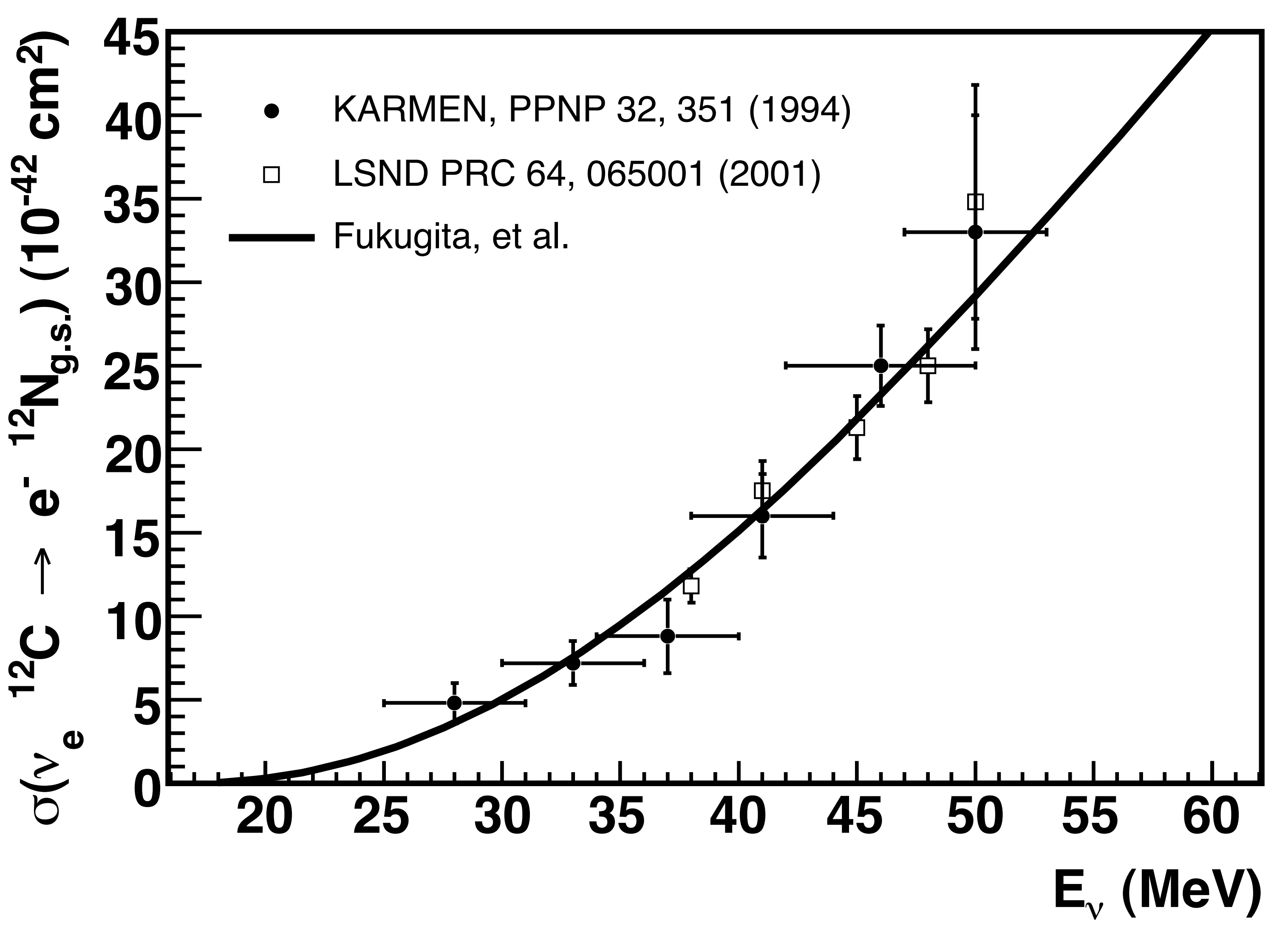
Fairly simple nuclei;
no bound excited states
Achievable errors « 10%

Gazit, Barnea, PRL 2007

No data to compare with

Neutrino-^{12}C Scattering

Experiment: Karmen and LSND

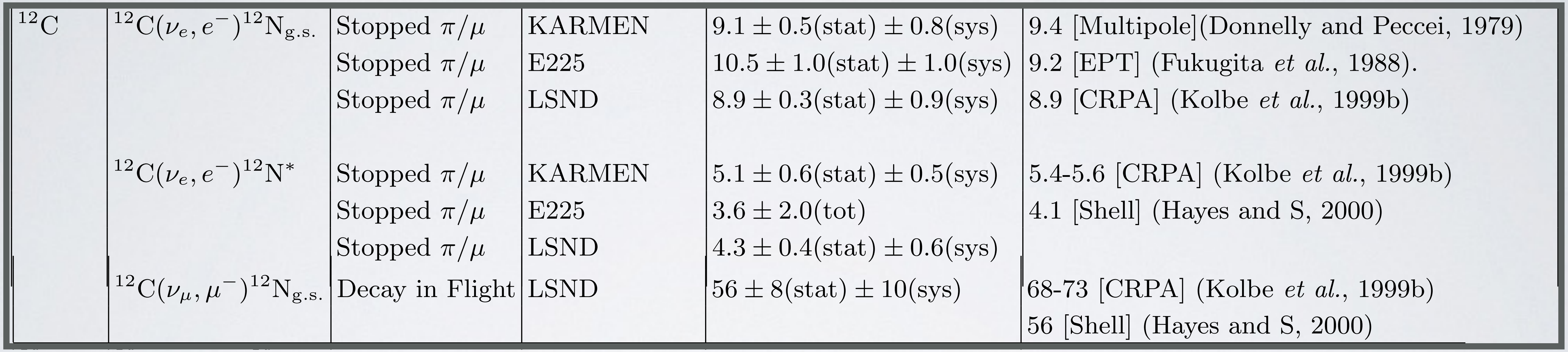


ν_e charged current to ^{12}N
from muon decay at rest

theory errors estimated at ~ 20 % , Fukugita et al., 1988

Neutrino-^{12}C Scattering

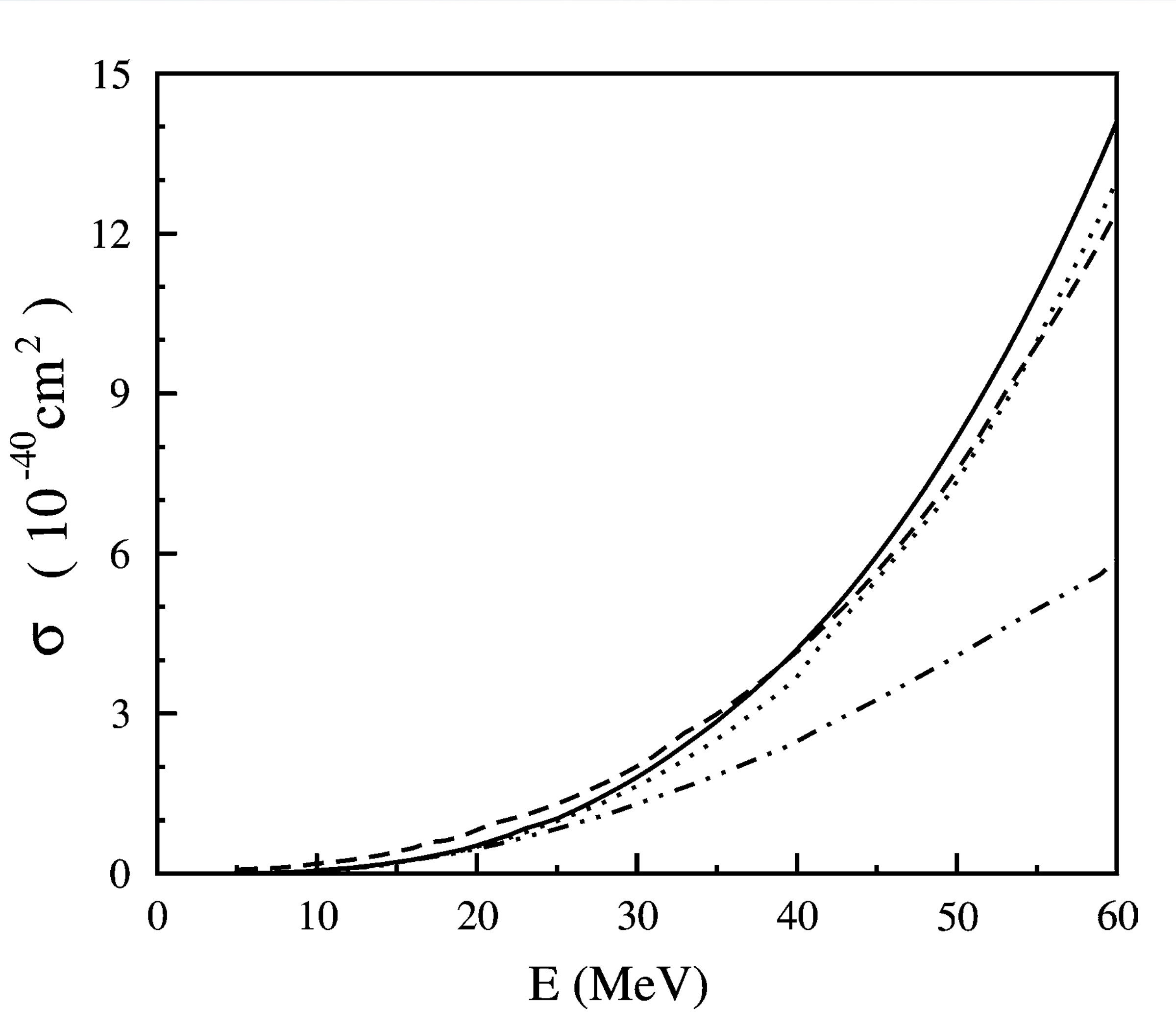
Neutrino charge current scattering
from ^{12}C (LSND/Karmen)



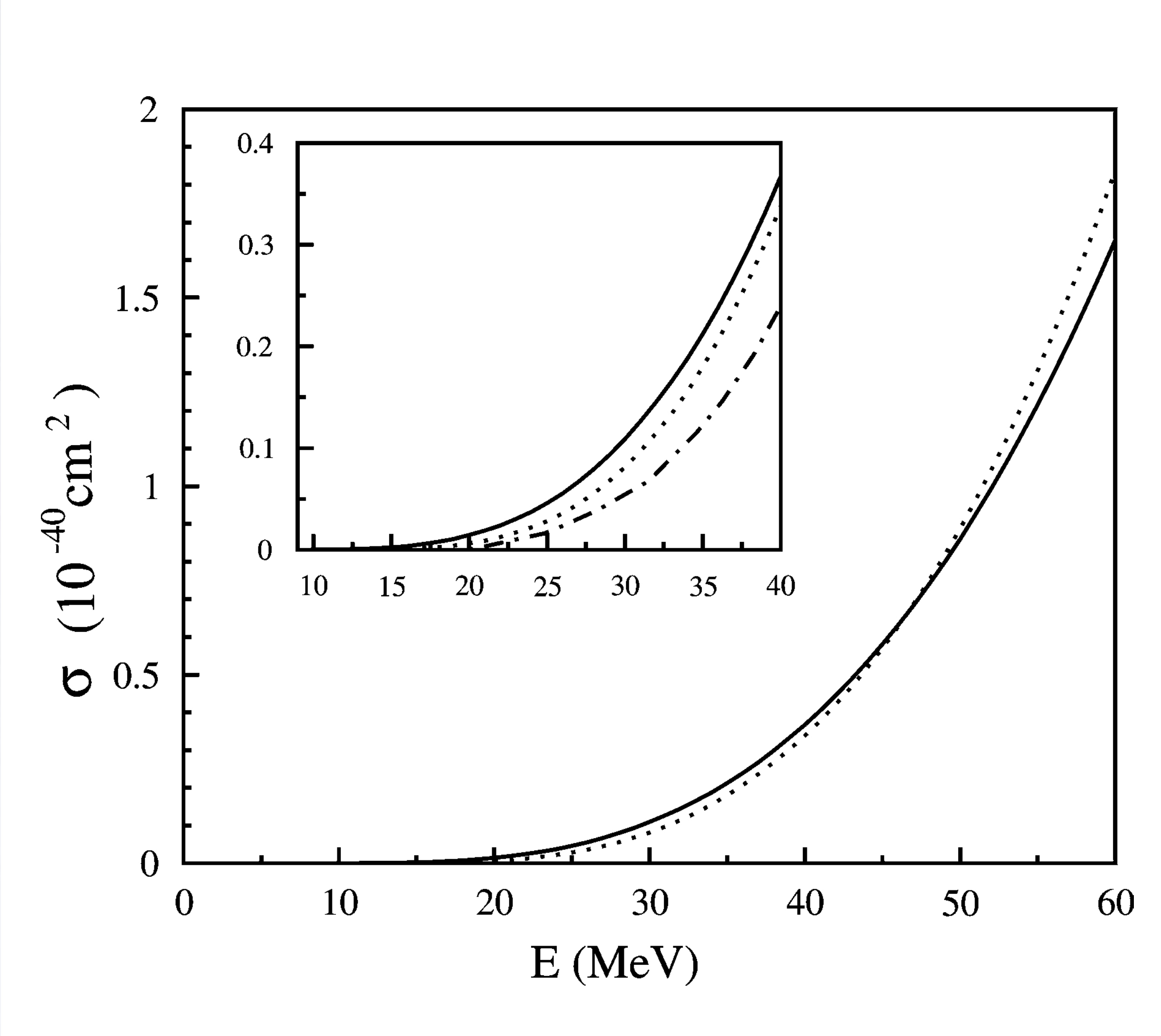
^{12}C	$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$	Stopped π/μ	KARMEN	$9.1 \pm 0.5(\mathrm{stat}) \pm 0.8(\mathrm{sys})$	9.4 [Multipole](Donnelly and Peccei, 1979)
		Stopped π/μ	E225	$10.5 \pm 1.0(\mathrm{stat}) \pm 1.0(\mathrm{sys})$	9.2 [EPT] (Fukugita *et al.*, 1988).
		Stopped π/μ	LSND	$8.9 \pm 0.3(\mathrm{stat}) \pm 0.9(\mathrm{sys})$	8.9 [CRPA] (Kolbe *et al.*, 1999b)
	$^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}^*$	Stopped π/μ	KARMEN	$5.1 \pm 0.6(\mathrm{stat}) \pm 0.5(\mathrm{sys})$	5.4-5.6 [CRPA] (Kolbe *et al.*, 1999b)
		Stopped π/μ	E225	$3.6 \pm 2.0(\mathrm{tot})$	4.1 [Shell] (Hayes and S, 2000)
		Stopped π/μ	LSND	$4.3 \pm 0.4(\mathrm{stat}) \pm 0.6(\mathrm{sys})$	
	$^{12}\mathrm{C}(\nu_\mu, \mu^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$	Decay in Flight	LSND	$56 \pm 8(\mathrm{stat}) \pm 10(\mathrm{sys})$	68-73 [CRPA] (Kolbe *et al.*, 1999b)
					56 [Shell] (Hayes and S, 2000)

Little evidence for important 2N current effects
for 30-100 MeV neutrinos

Neutrino - Ar Scattering



inclusive υ_e charged current ^{40}Ar
Athar, et al, 2004



anti-ν charged current to Cl

Significant differences

Neutrinos in Matter

- Many studies in mean-field models, perhaps accurate enough in many cases
- Virial expansion should be accurate inhot dilute matter
- Should use same interactions/currents in nuclei and matter. More reliable constraints.
- Matter results are less directly connected to experiment for astrophysical energies, particularly for very neutron-rich matter.

Can we identify important regimes where more accuracy is required; similarities in nuclear and matter responses?

Status and Outlook

- Microscopic inputs reasonably well defined (interactions, currents)
- Future inputs on one- and two-nucleon level from lattice QCD
- Accurate calculations possible in light nuclei
- Critical for accelerator neutrino energies
- What future experiments on nuclei are most valuable?
- More realistic studies of neutrinos in matter (Reddy, Schwenk, …)