An Experimentalist's View of Neutrino-Nucleus QE Scattering

Fermilab
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Outline

- What is quasi elastic scattering (QES)?
- Why has Neutrino Nucleus QES Become Interesting?
- Inclusive Electron QES; Formalism and Results.
  (longitudinal and transverse, scaling)
- Extension to neutrino-nucleus QES.
- Fails to work.
- Differences between electron and neutrino QES experiments.
- The question of the day??
- How about determining the neutrino flux?

• QES is a paradigm in which elastic lepton-nucleon (free or merely charge changing n < -- >p) scattering is applied to the scattering off individual nucleons in the nucleus. It requires a 3-momentum transfer q > ~ 0.3GeV/c, to resolve an individual nucleon . The cross-section is ~ to the square of the incoherent sum of the scattering amplitudes off the individual nucleons.

• Electron-nucleus QES has been studied for many years and has exposed many important aspects of nuclear structure.

• The extension of QES (CCQE) $(\nu_l + n \rightarrow l^- + p,\ \bar{\nu}_l + p \rightarrow l^+ + n)$ to neutrino- nucleus scattering has become quite important.

For $0.3 < E_\nu < 3.0$ GeV it is the dominant interaction.

CCQE is treated as readily identifiable and the cross section readily calculable.

Some 40 calculations published since 2005

CCQE is typically used in investigations of neutrino oscillations as it provides essential information for neutrino oscillations, flavor and energy.

$E_{osc}(\text{GeV}) \sim L(\text{km})/\Delta m^2(\text{ev}^2)$ $10^3/10^3$, 1/1

It's measured yield is difficult to reconcile with calculation

The Nucleus

A finite aggregate of nucleons interacting via strong, complex short range two-body forces.

$$H = \sum_i \frac{p_i^2}{2m_i} + V_{i,j} \rightarrow \sum_i \frac{p_i^2}{2m_i} + V(r_i) + \sum_{i>j} V_{eff}(r_{i,j})$$

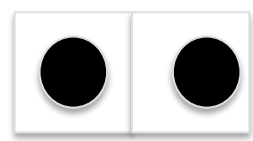
Nuclear density is approximately constant, $R = r_0 A^{1/3}$, with spin 1/2 neutrons and protons, thus 4 particles can be put into each volume element of phase space $p < p_0$.

$$4\frac{4\pi}{3}\left(\frac{p_0}{2\pi\hbar}\right)^3 = \frac{A}{V} \qquad V = \frac{4\pi}{3} A r_0^3 \qquad r_0 = 1.2 \bullet 10^{-13} cm$$

$$p_0 \equiv p_F = 250 MeV/c, \quad E_F = 34 MeV$$

Nucleons have a diameter of 1.25f. The mean separation of nucleons in a nucleus

$$\left(\frac{V}{A}\right)^{\frac{1}{3}} = \left(\frac{4\pi A(1.2)^3}{3A}\right) = 1.93 f$$

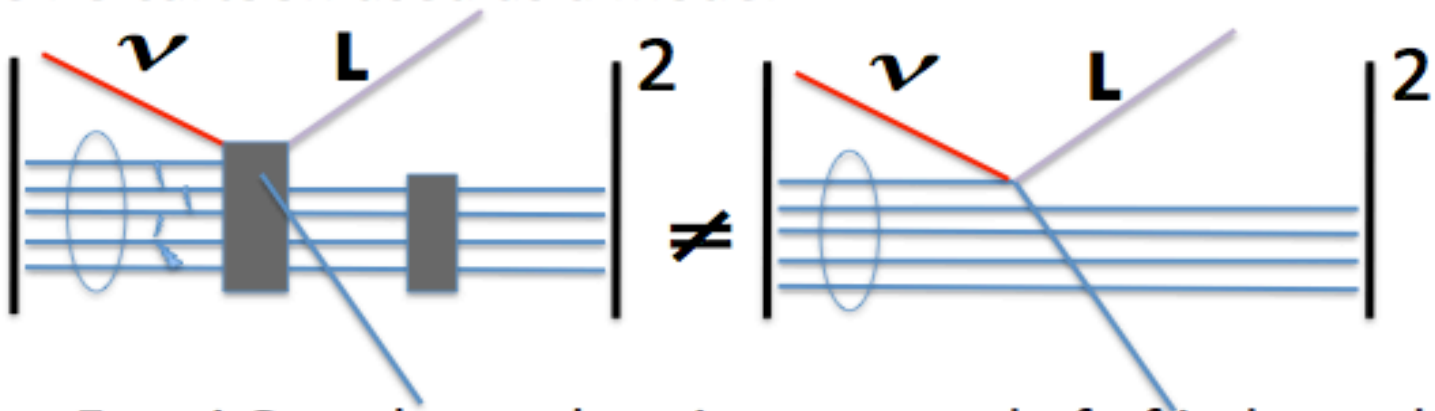


Looks like there is every reason to suspect that the nucleons may not act as independent particles confined by an average potential.

Calculating the QE Cross Section

- "Quasi-Elastic Scattering" is the dominant process in this domain and the "easiest to calculate". But it's a poor model.

- The FG cartoon used as a model



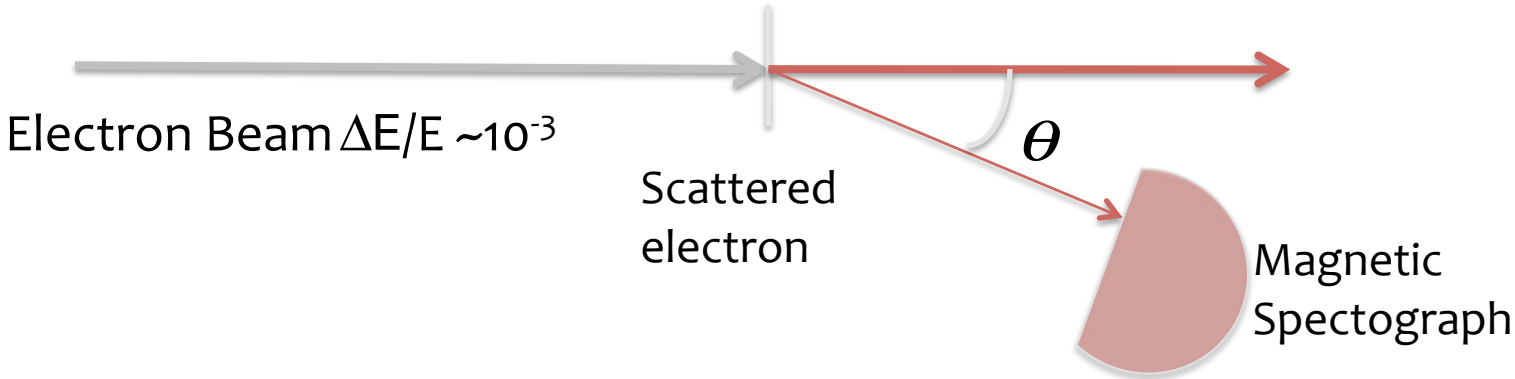
- In a Fermi Gas, the nucleus is composed of of independent nucleons each with a specified momentum and a single negative energy($-E_S$). $\left(E_\nu - E_L = \omega = E_N - M_N - (-E_S)\right)$

- Model refined by use of a Spectral Function

$$S(\mathbf{q},\omega) = \sum_n |\langle n| \sum_{\mathbf{k}} a^\dagger_{\mathbf{k}+\mathbf{q}} a_{\mathbf{k}} |0\rangle|^2 \delta(\omega + E_0 - E_n) \ .$$

$$S_{IA}(\mathbf{q},\omega) = \int d^3k \, dE \, P_h(\mathbf{k},E) P_p(\mathbf{k}+\mathbf{q},\omega - E)$$

Inclusive Electron Scattering



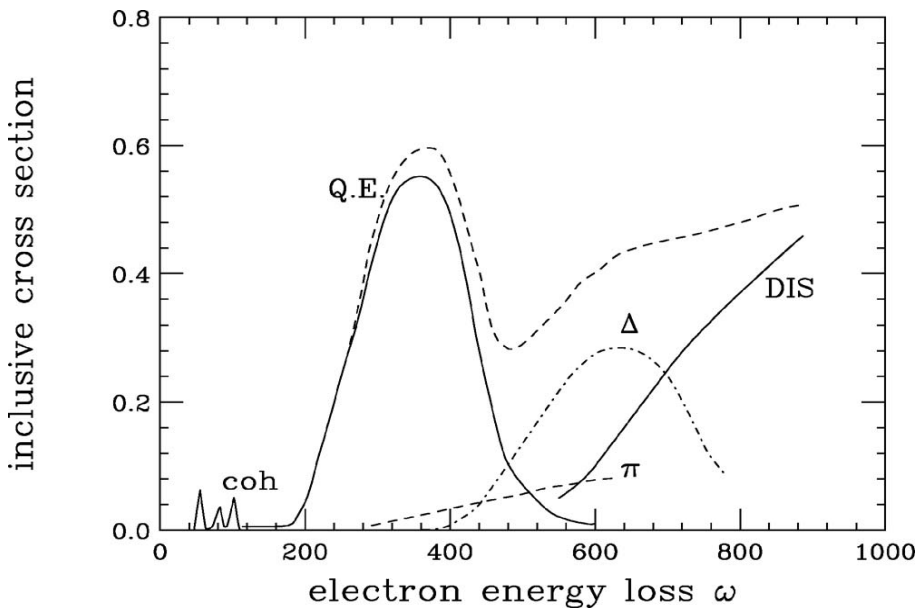


FIG. 1. Schematic representation of inclusive cross section as a function of energy loss.

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

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

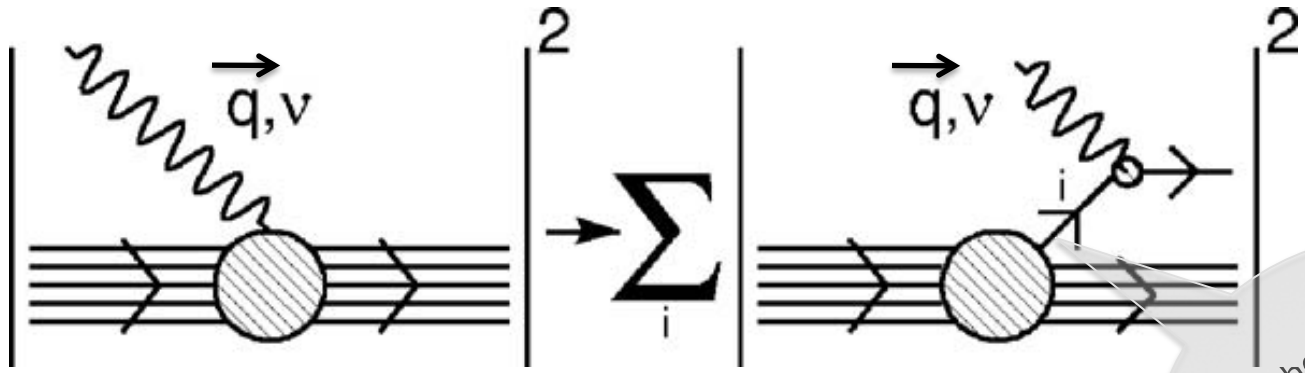
$$\vec{q} = \vec{p} - \vec{p}'$$

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

Quasi-Elastic Electron Scattering

True Complexity

Simple QE Model



Incoherent sum over individual nucleons

$$Q^2 = q^2 - \omega^2$$

$$\tau^2 = \frac{Q^2}{4M^2}$$

$$\frac{d\sigma^2}{d\Omega_e d\omega} = \left(\frac{d\sigma}{d\Omega_e}\right)_{Mott}\left\{\left(\frac{Q}{|\vec{q}|}\right)^4 R_L(|\vec{q}|,\omega) + \left(\frac{1}{2}\left(\frac{Q}{|\vec{q}|}\right)^2 + \tan^2\frac{\theta}{2}\right)R_T(|\vec{q}|,\omega)\right\}$$

$$(d\sigma/d\Omega_e)_{Mott} = \alpha^2\cos^2(\theta/2)/E\sin^4(\theta/2)$$

$$\langle p',N|J_\mu|p,N\rangle = \frac{i}{\Omega} < \bar{u}_N(p')|[F_1^N(q^2)\gamma_\mu + F_2^N(q^2)\sigma_{\mu\nu}q_\nu]|u_N(p) >$$

$$F_i^{\tau_3}(q^2) = \frac{1}{2}(F_i^S(q^2) + \tau_3 F_i^V(q^2)) \qquad 2mF_2^S(0) = \mu'_p + \mu_n = -0.120$$

$$F_1^S(0) = 1 \qquad F_1^V(0)=1 \qquad 2mF_2^V(0) = \mu'_p - \mu_n = +3.706$$

$$\frac{d\sigma}{d\Omega_e} = \sigma_{Mott}\frac{E'}{E_0}\left[\frac{G_E^{N,2}(q^2) + \tau G_M^{N,2}(q^2)}{1+\tau} + 2\tau G_M^2(q^2)\tan^2(\frac{\theta}{2})\right]$$

$$G_E(q^2) = F_1(q^2) + \tau F_2(q^2) \qquad G_M(q^2) = F_1(q^2) + F_2(q^2)$$

Scaling in Electron Quasielastic Scattering (1)

The energy given up by the electron, to nucleon with initial momentum $\vec{k}$

$$\omega = T_N + E_s + E_R$$

T_N is the kinetic energy of the struck nucleon, E_s the separation energy of the struck nucleon, E_R the recoil kinetic energy of the nucleus.

$$\omega = [(\vec{k} + \vec{q})^2 + m^2]^{\frac{1}{2}} - m + E_s + E_{recoil}$$

$$= [k_{\parallel}^2 + 2k_{\parallel}q + q^2 + k_{\perp}^2 + m^2]^{\frac{1}{2}} - m + E_s + E_{recoil}$$

$$neglect\ E_s,\ E_{recoil}, k_{\perp}$$

$$k_{\parallel} = \sqrt{\omega^2 + 2m\omega} - q \equiv y$$

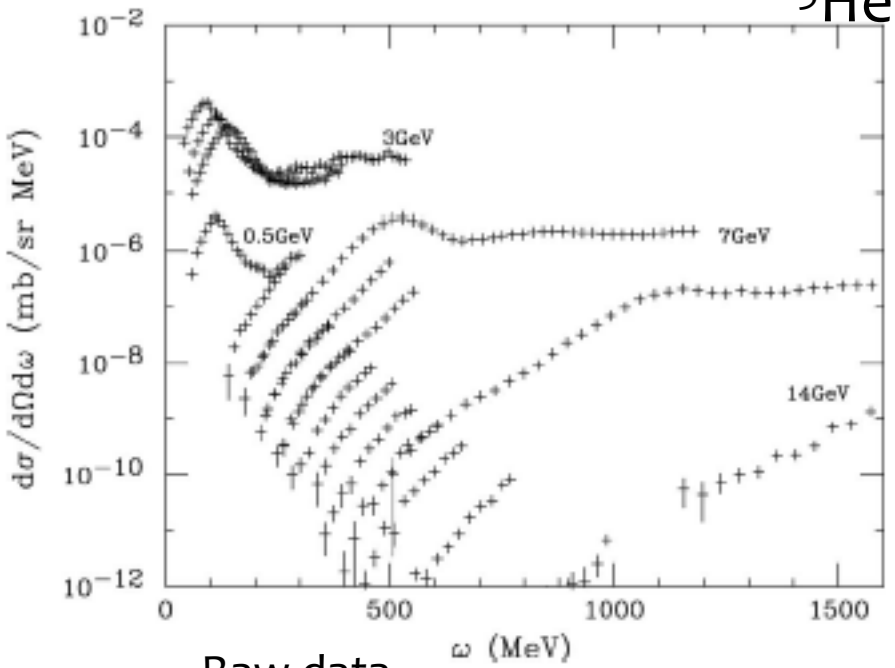
Instead of presenting the data as a function of q and ω, it can be expressed in terms of a single variable y

$$F(y,q) = \left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{EXP} \left(\frac{1}{Z\sigma_{ep}(q) + N\sigma_{en}(q)}\right)\frac{d\omega}{dy}$$

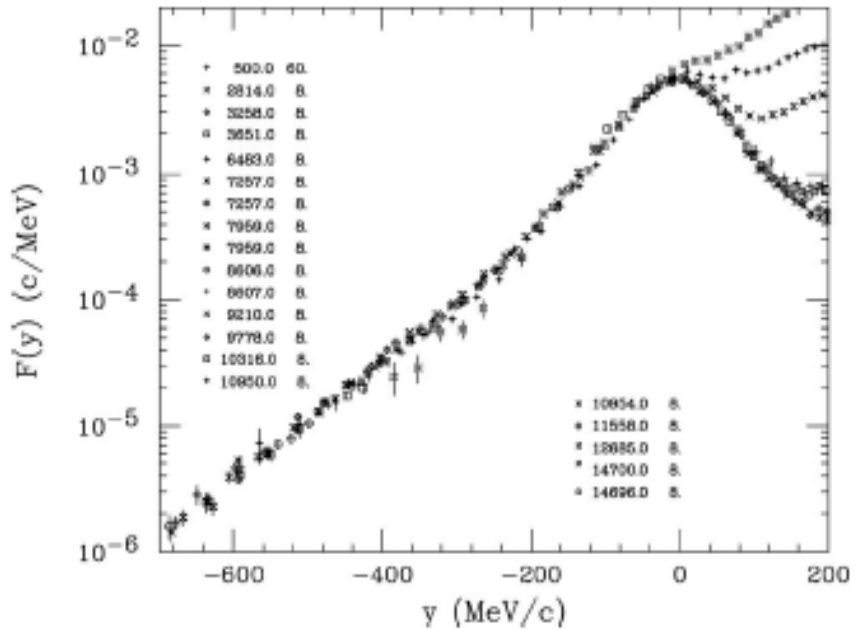
The scaling function $F(y,q)$ is formed from the measured cross section at 3 momentum transfer q dividing out the incoherent single nucleon contributions at that three momentum transfer.

Scaling in Electron Quasielastic Scattering (2)

^{3}He



Raw data



Scaled

$$y = \sqrt{\omega^2 + 2m\omega} - q = 0$$

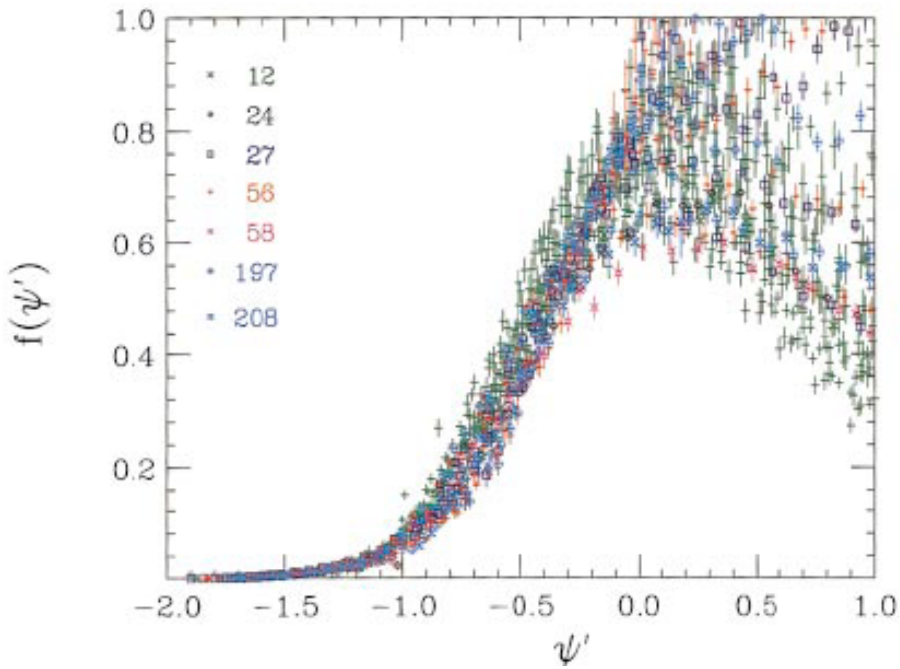
$$q^2 = \omega^2 + 2m\omega = \omega^2 + Q^2$$ kinimatics for scattering off a nucleon at rest

$y < 0$, when the energy transfer (ω) is less than it is for 3-momentum tranfer q to a free nucleon at rest.

Excuses for failure y>0: meson exchange, pion production, tail of the delta.

Super Scaling

The fact that the nuclear density is nearly constant for A ≥ 12 leads one to ask, can scaling results be applied from 1 nucleus to another? W.M. Alberico, et al Phys. Rev. **C38**, 1801(1988), T.W. Donnelly and I. Sick, Phys. Rev. **C60**, 065502 (1999)



A new dimentionless scaling variable is employed

$$\psi = \frac{y_{RFG}}{k_{Fermi}} = \frac{m_N}{k_{Fermi}}(\lambda\sqrt{1+\tau^{-1}} - \kappa)$$

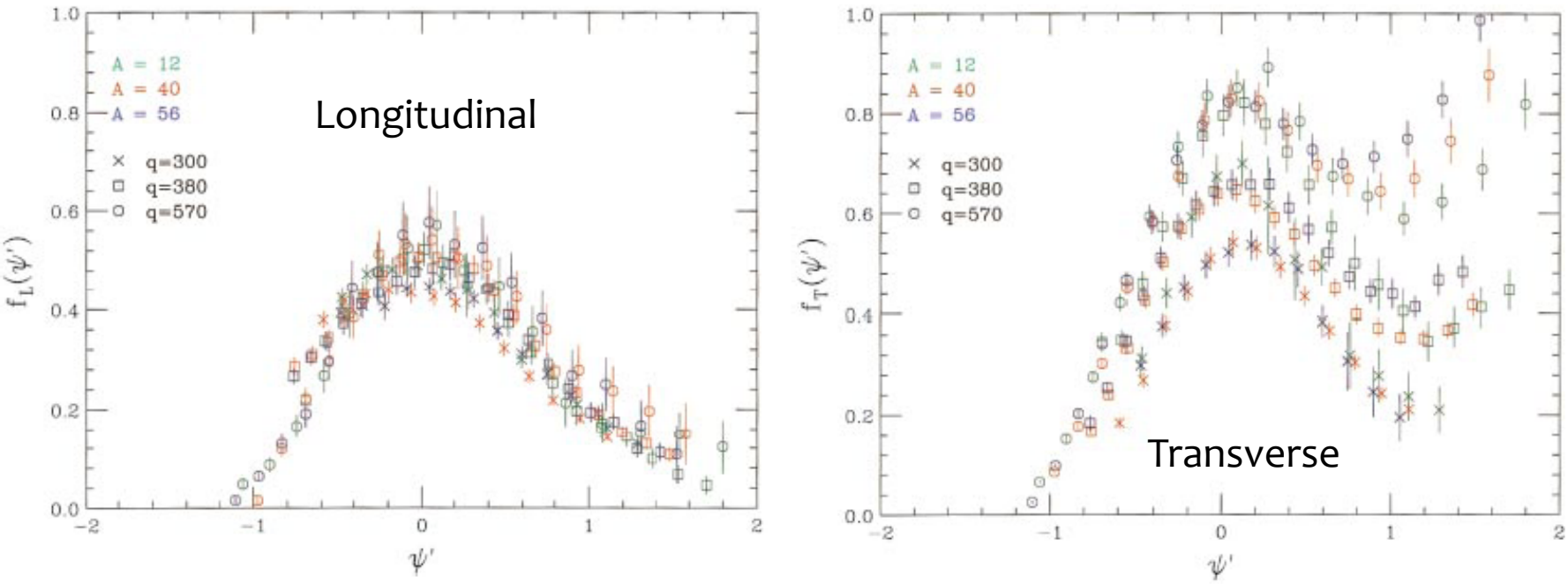
$$\lambda = \omega / 2m_N, \tau = Q^2 / 4m_N^2, \ \kappa = q / 2m$$

Note linear scale: not bad for

$$\psi < 0$$

Serious divergence above $\psi = 0$

Separating Scaling into its Longitudinal and Transverse Responses Phys. Rev. **C60**, 065502 (1999)



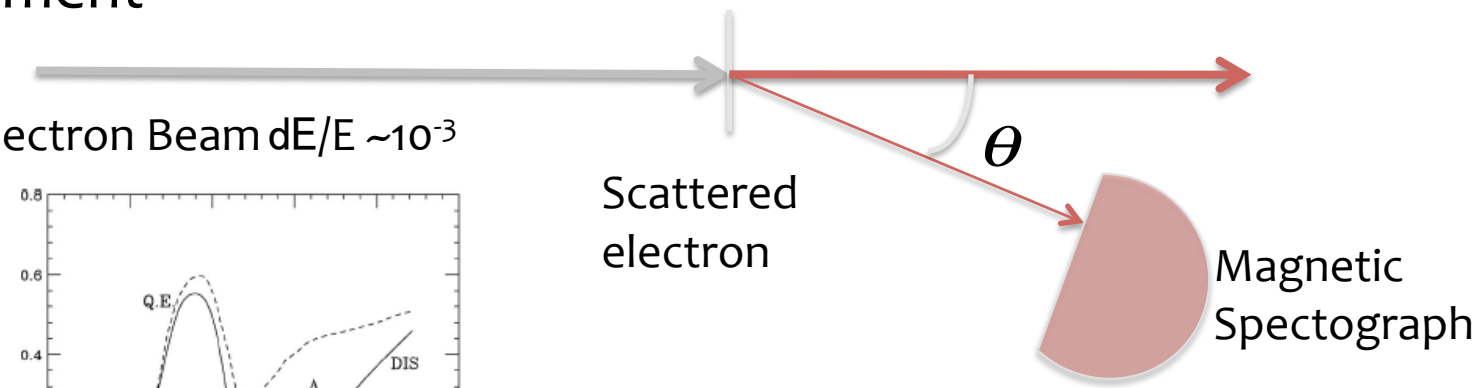
The responses are normalized so that in Relativistic Fermi Gas:

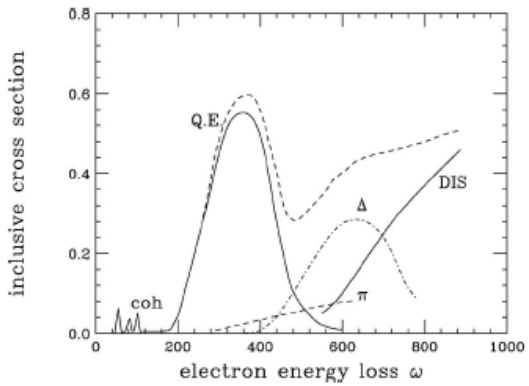
$$f_L(\psi) = f_T(\psi) \text{???}$$

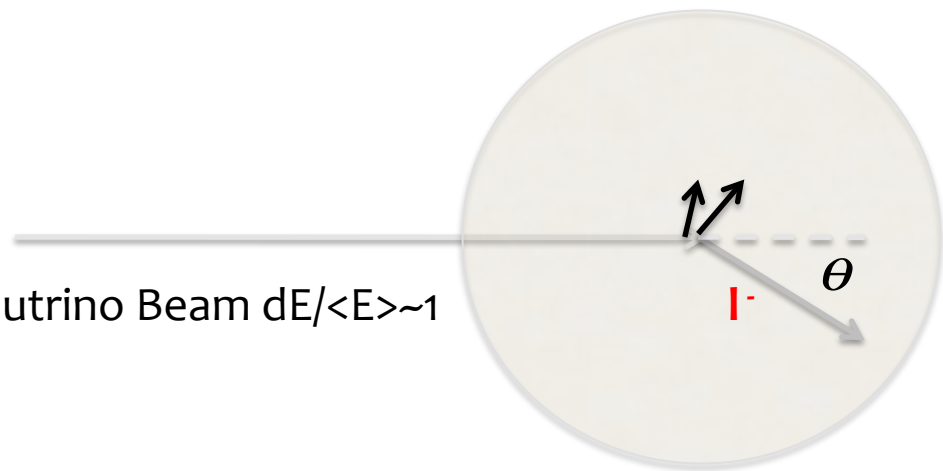
f_L satisfies the expected Coulomb sum rule. ie. It has the expected value. f_T has mostly excuses (tail of the Δ, meson exchange, pion production etc.) Note divergence below ψ'=0

Finally Neutrinos

Experiment







What's ω ?????

Don't know E_ν

What's q ????

Very Different Situation from <u>inclusive</u> electron scattering

Neutrino (+), Anti-Neutrino(-) Nucleon Cross Section

Charged lepton mass=0

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\left\{A(Q^2) \pm B(Q^2)\left[\frac{s-u}{M^2}\right] + C(Q^2)\left[\frac{s-u}{M^2}\right]^2\right\}$$

$$A(Q^2) = \frac{Q^2}{4}\left[f_1^2\left(\frac{Q^2}{M^2} - 4\right) + f_1 f_2\left(\frac{4Q^2}{M^2}\right) + f_2^2\left(\frac{Q^2}{M^2} - \frac{Q^4}{4M^4}\right) + g_1^2\left(4 + \frac{Q^2}{M^2}\right)\right]$$

$$\left.\begin{aligned} B(Q^2) &= Q^2(f_1 + f_2)g_1 \\ C(Q^2) &= \frac{M^2}{4}\left(f_1^2 + f_2^2\frac{Q^2}{4M^2} + g_1^2\right) \end{aligned}\right\}\text{Most important terms}$$

$$s - u = 4ME_\nu + Q^2$$

Cross Section in some $\lim$ *iting cases*

$$\frac{d\sigma}{dQ^2}\Big|_{Q^2\to 0} = \frac{G_F^2\cos^2\theta_C}{2\pi}\left(f_1^2(0) + g_1^2(0)\right)$$

$$\frac{d\sigma}{dQ^2}\Big|_{E_\nu\to\infty} = \frac{G_F^2\cos^2\theta_C}{2\pi}\left(f_1^2(Q^2) + f_2^2(Q^2)\frac{Q^2}{4M^2} + g_1^2(Q^2)\right)$$

C.H. Llewellyn-Smith, Phys Reports ***3****,261 (1972)*

Neutrino , Anti-Neutrino Nucleon Cross Section (cont)

<u>Values for the form Factors</u>

$$f_1(q^2) = \left[(G_E^p - G_E^n) + \frac{Q^2}{4M^2}(G_M^p - G_M^n) \right] \left(1 + \frac{Q^2}{4M^2} \right)^{-1}$$

$$\cong \frac{\left(1 + \frac{Q^2}{4M^2}(1 + \mu_p - \mu_n \right)}{\left(1 + \frac{Q^2}{4M^2} \right)\left(1 + \frac{Q^2}{m_V^2} \right)^2} \qquad \mu_p = 1.793,\ \mu_n = -1.913,\ m_V^2 = 0.71 GeV^2$$

$$f_2(q^2) \cong \frac{\left(\mu_p - \mu_n \right)}{\left(1 + \frac{Q^2}{4M^2} \right)\left(1 + \frac{Q^2}{m_V^2} \right)^2}$$

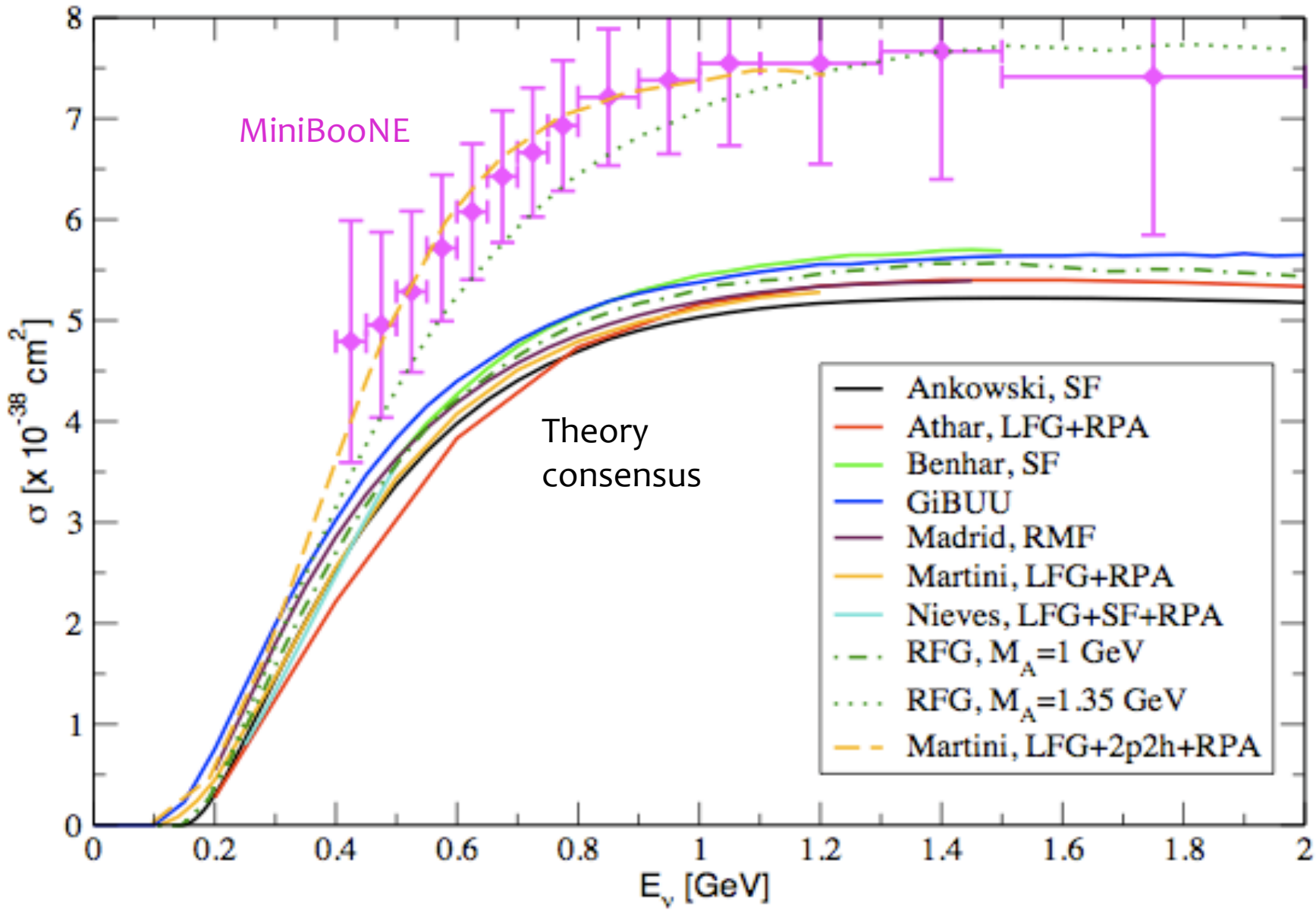
$$g_1(q^2) \cong 1.269 \left(1 + \frac{Q^2}{m_A^2} \right)^2 \qquad m_A^2 = 1.02 GeV^2$$

The above dipole form factors are good up to $Q^2 \cong 1GeV$. *Thus the total weak current used for* QE *scattering is the sum of individual one body nucleon curents*

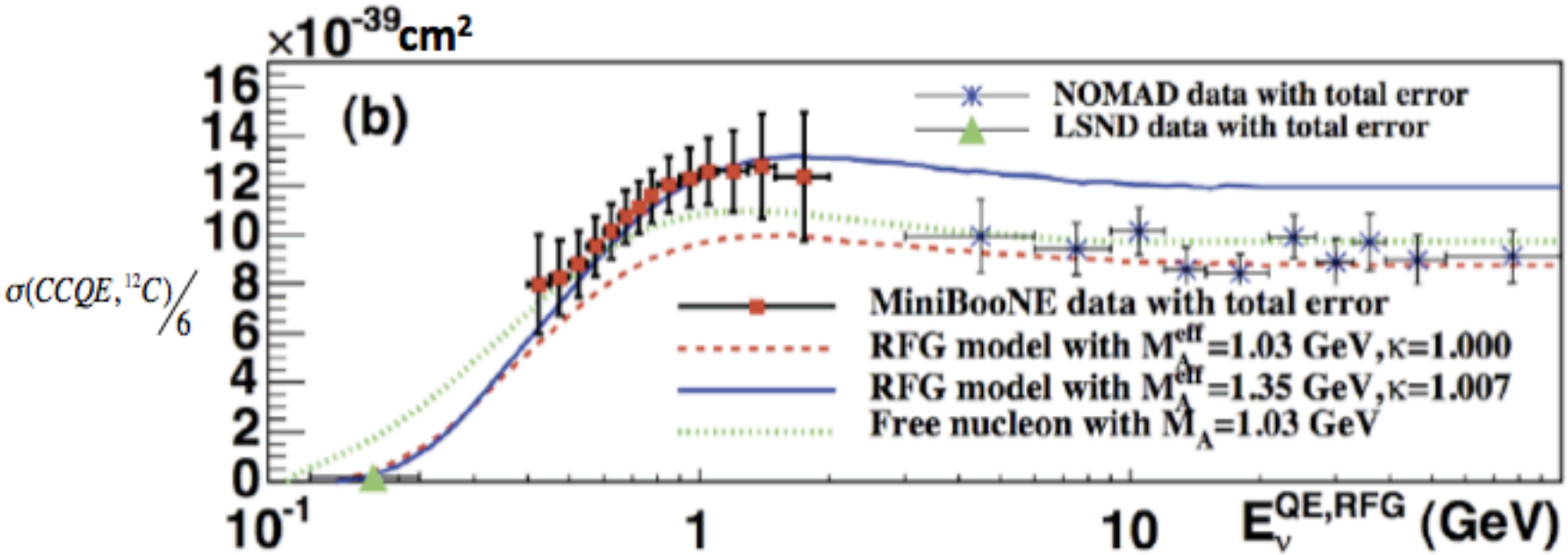
$$J_N = \sum_{I=1}^{A} j_I^n = \sum_{1}^{A} \bar{u}_i^{n'}(p') \left[f_1 \gamma^\mu + \frac{i}{2m_n} f_2 \sigma^{\mu\nu} Q_\nu + g_1 \gamma^\mu \gamma_5 + \frac{1}{2m_n} g_p Q^\mu \gamma_5 \right] u_i^n(p)$$

The neutrino-nucleus cross section is then fixed by convoluting the scalar product of these one body currents with the lepton current and integrating over the initial momentum distribution of the nucleons in the nucleus.

What is Observed? CCQE $\nu_\mu + {}^{12}C \rightarrow \mu + 7p, 5n(\cancel{\pi})$



MiniBooNE's "CCQE" Data for $\nu_\mu + {}^{12}C \rightarrow \mu^- + (7p,5n)$



How can the cross section exceed that of the free neutron???

Omar Benhar arXiv:1012.2032v1 [nucl-th]

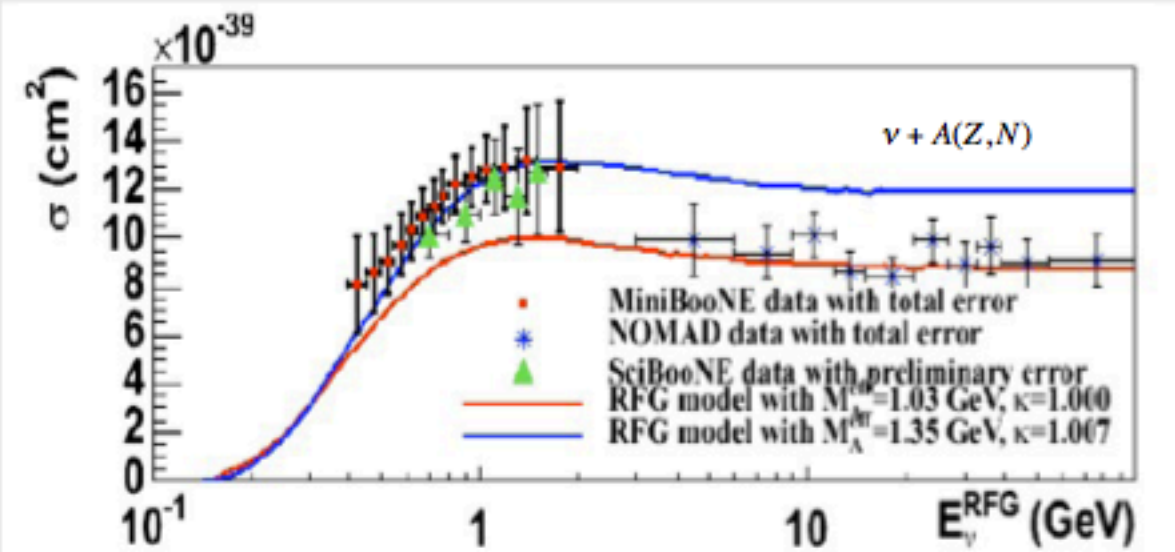
"A new paradigm, suitable for studies of neutrino interactions, should be based on a more flexible model of nuclear effects, yielding a realistic description of the broad kinematical range associated with the relevant neutrino energies".

Other Experimental Results for neutrino CCQE

SciBooNE CCQE results

CCQE results from SciBooNE

- SciBooNE: (highly segmented) scibar in Booster nu beam at FNAL (as MiniBooNE)
- (preliminary) results indicate higher cross section as seen by MiniBooNE (arXiv:0909.5647)



Experiment	Target	Cut in Q^2 [GeV^2]	$M_A[GeV]$
K2K[4]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[5]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS[6]	iron	no cut	1.19 ± 0.17
MINOS[6]	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE[7]	carbon	no cut	1.35 ± 0.17
MiniBooNE[7]	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD[8]	carbon	no cut	1.07 ± 0.07

TABLE I. Recent M_A measurements

arXiv:1007.2195

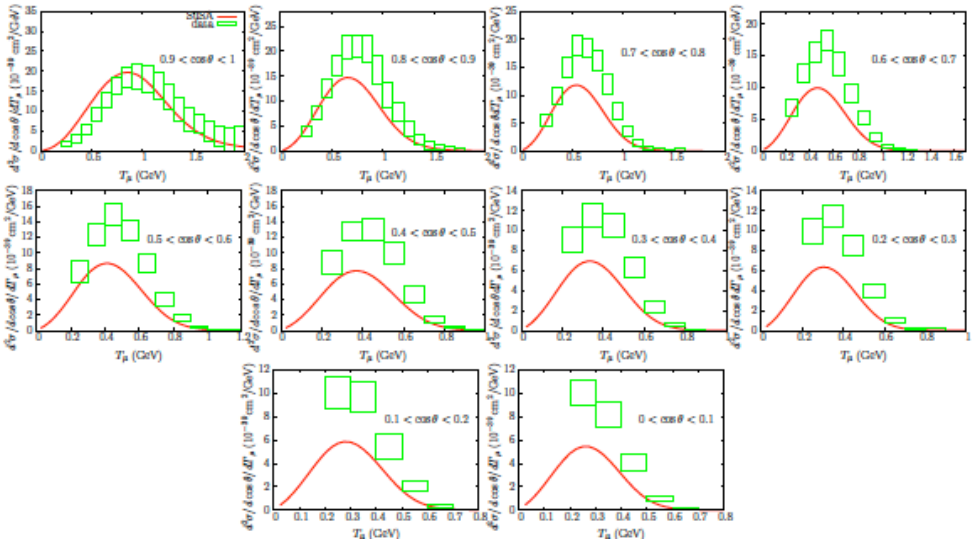
Generally: Large value of M_A required to fit both the Q^2 dependence and the larger than expected yield.

Further Reaction

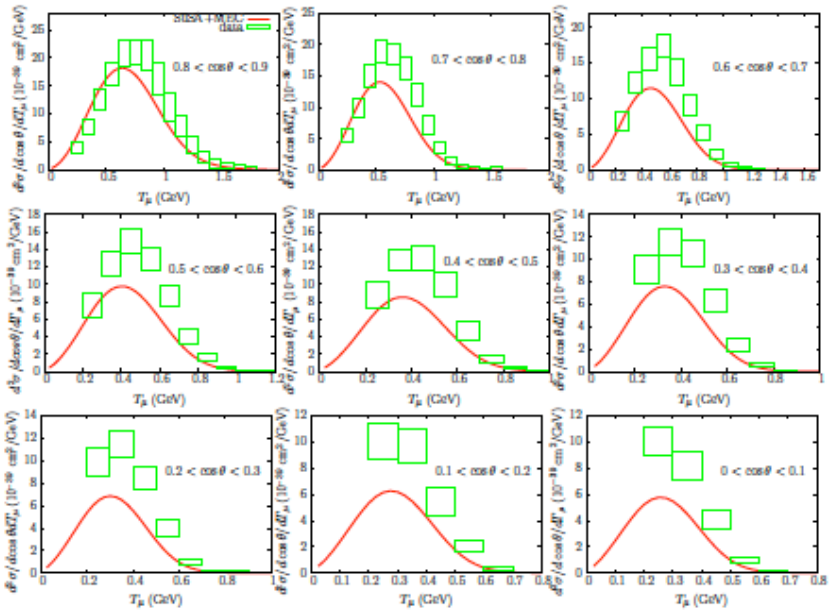
Amaro et al; Phys. Lett. **B696** 151(2011). arXiv:1010.1708 [nucl-th]

Included Meson Exchange into their SuperScaling (L) Approach

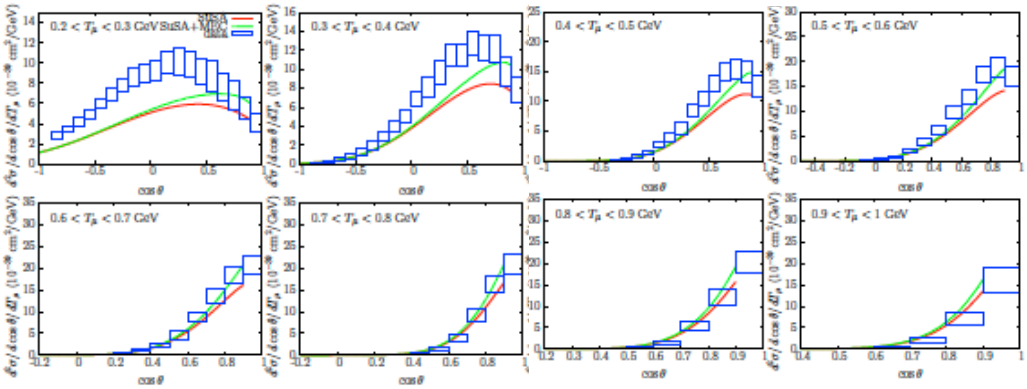
Straight impulse App.



Meson Exchange Included



Angular Dependence



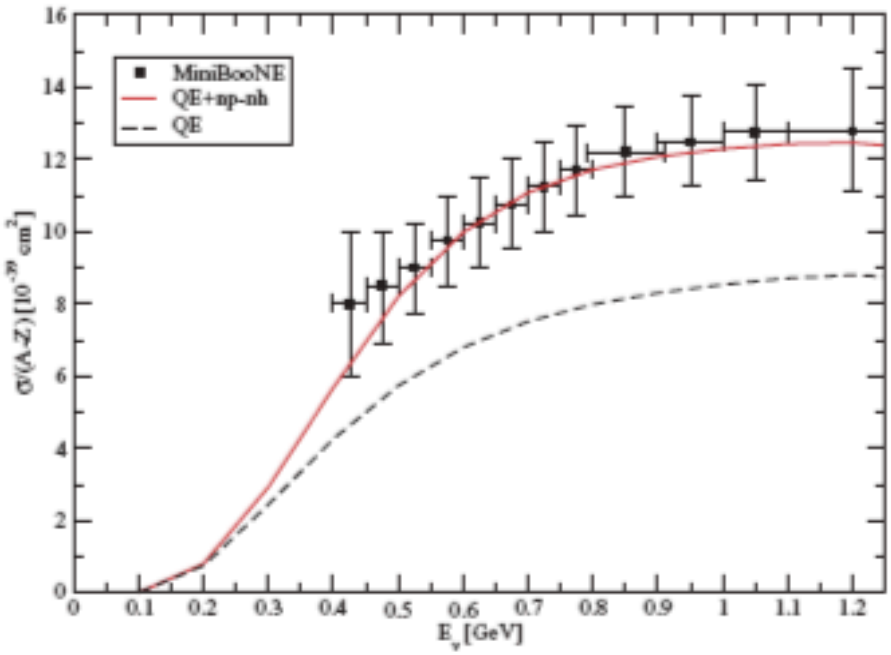
Experimental Caveats

- Flux Uncertainty
- Inadequate subtraction of pion absorption following resonance formation
- Inclusion of low Q^2 that cannot be QE
- Incorrect determination of detector efficiency
- Many of above are included in the error band

Even More Surprising - Theoretical Support

M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PHYS. REV. **C 80**, 065501 (2009)

They use M_A=1.03 GeV, in an RPA formalism

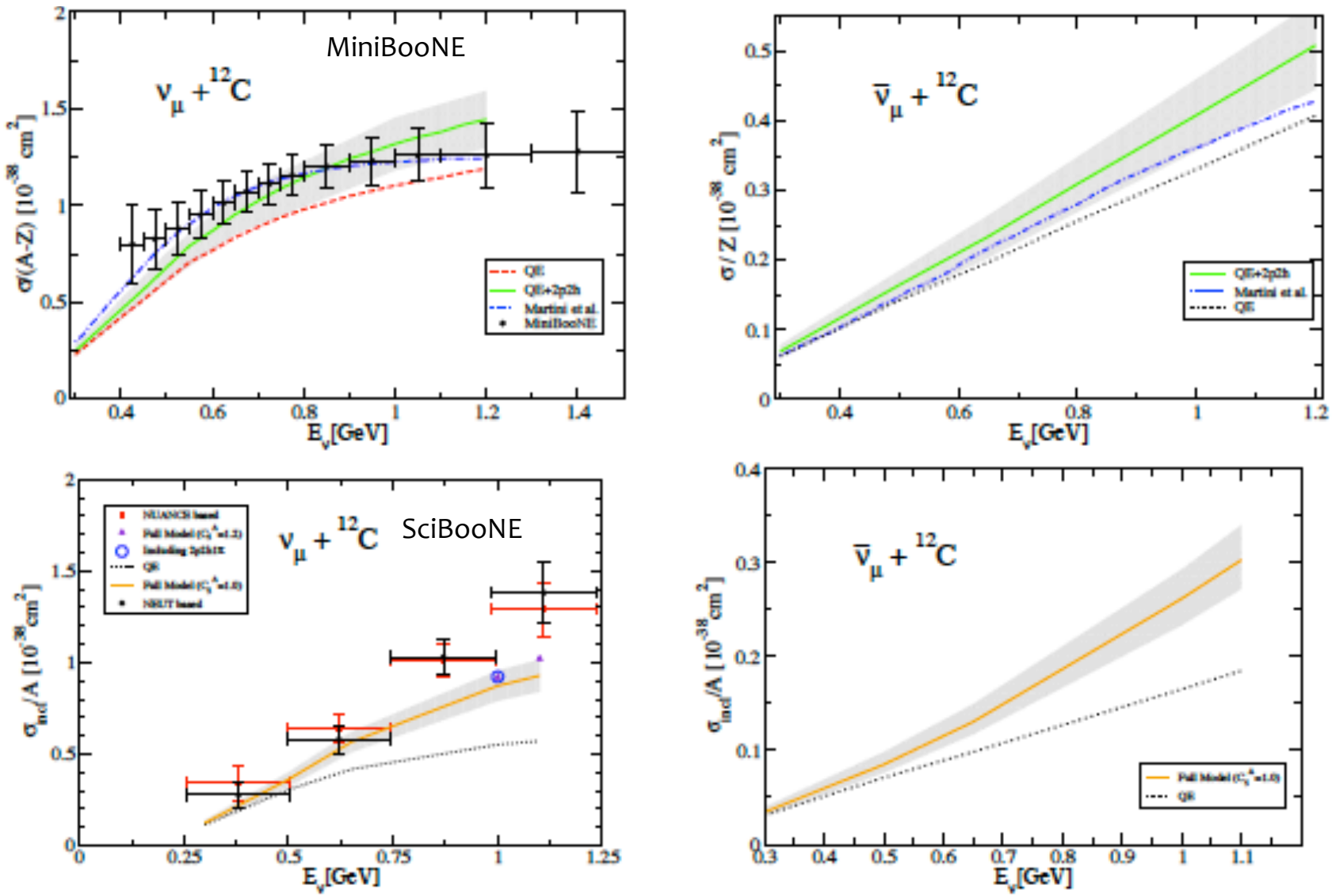


"We suggest that the proposed increase of the axial mass from the standard value to a larger one to account for the quasielastic data, reflects the presence of a polarization cloud, mostly due to tensor interaction, which surrounds a nucleon in the nuclear medium. It translates into a final state with ejection of two nucleons, which in the present stage of the experiments is indistinguishable from the quasielastic final state."

$$\sigma_{\nu(\bar{\nu})} \approx V_L^2 + V_T^2 + (-)2V_T A_T + A_T^2$$

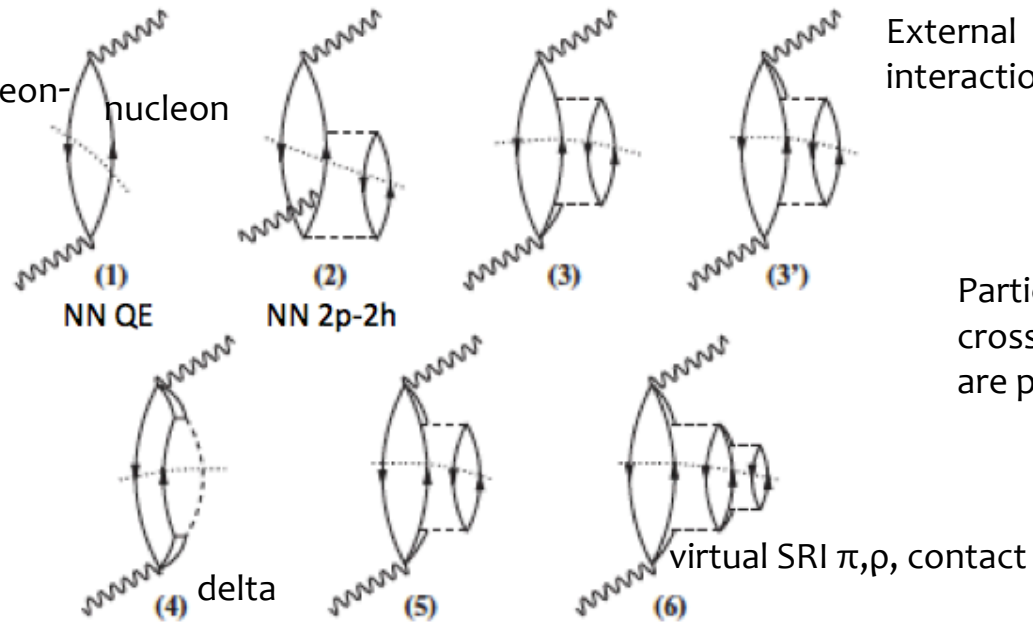
A New Result (as of Feb 14)

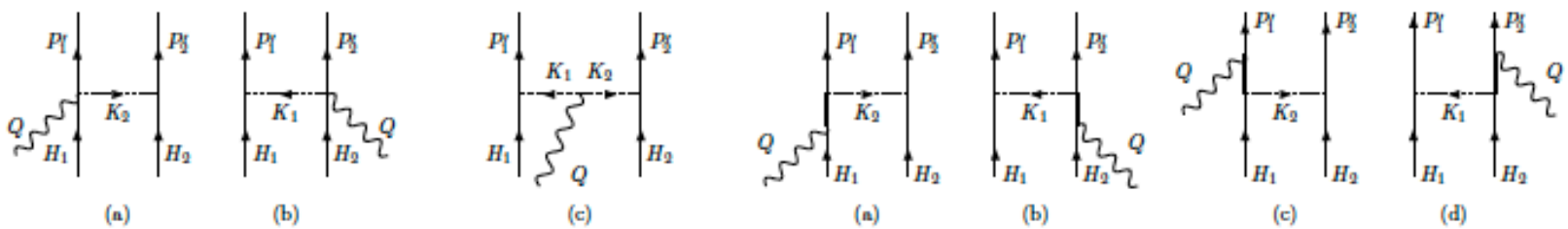
J.Nieves, I. Ruiz and M.J. Vincente Vacas arXiv: 1102.2777 [hep-ph]



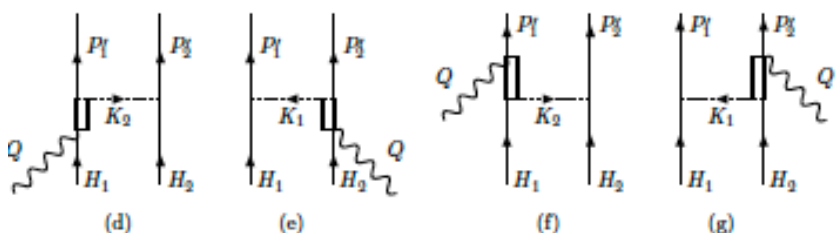
Diagrams of Some Short Range Correlations

Some p-h diagrams from Martini et al. PR **C80**, 065501





Correlation



Exchange

Exchange Current and pionic correlation diagrams in Amaro et al. **PR C82** 044601

Comments on RPA

- RPA treats excitations of a many body system as a superposition of particle-hole (p-h) excitations. Particles are above the Fermi surface, holes are below

- The present series of talks had an excellent presentation of the neutrino-nucleus scattering in RPA by Marcos Martini and Magda Ericson. http://minerva-docdb.fnal.gov/0054/005431/001/martini_fermilab.pdf

- Their RPA calculation showed excellent agreement with MiniBooNE data, particulary the CCQE measurement of ν+C which had a disturbing x factor (1.4).

- it is to be expected that the observed CCOE cross section is larger than computed using what had been learned from inclusive electron scattering.

- The surprise is that the cross section per neutron in C exceeds the free neutron cross section. This issue was not remarked on and raises the question if this is possible

Can the CCQE Cross Section/N Exceed the Free N Cross Section?

PHYSICAL REVIEW C, VOLUME 65, 024002

Let's return to scaling of inclusive electron scattering

$$y = \sqrt{\omega^2 + 2m\omega} - q$$ Scaling variable

$$F(y,q) = \left(\frac{d^2\sigma}{d\Omega d\omega}\right)_{EXP} \left(\frac{1}{Z\sigma_{ep}(q) + N\sigma_{en}(q)}\right)\frac{d\omega}{dy}$$ Scaling function

$$\frac{d\sigma^2}{d\Omega_e d\omega} = \left(\frac{d\sigma}{d\Omega_e}\right)_{Mott} \left\{\left(\frac{Q}{|\vec{q}|}\right)^4 R_L(|\vec{q}|,\omega) + \left(\frac{1}{2}\left(\frac{Q}{|\vec{q}|}\right)^2 + \tan^2\frac{\theta}{2}\right) R_T(|\vec{q}|,\omega)\right\}$$ Longitudinal-Transverse

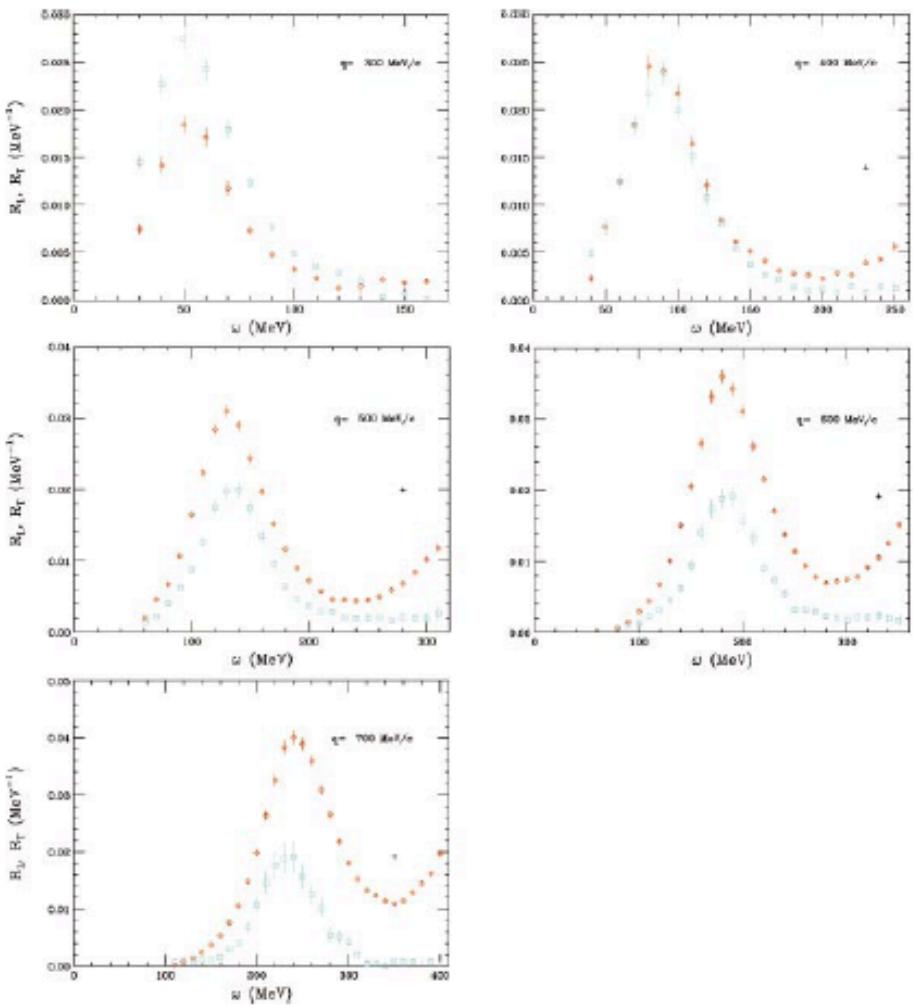
$$f_{L,T} = k_F \frac{R_{L,T}}{G_{L,T}}$$ In Relativistic FG $f_L = f_T$

$$G_L = \frac{qm}{Q^2}\left(ZG_{Ep}^2 + NG_{En}^2\right)$$

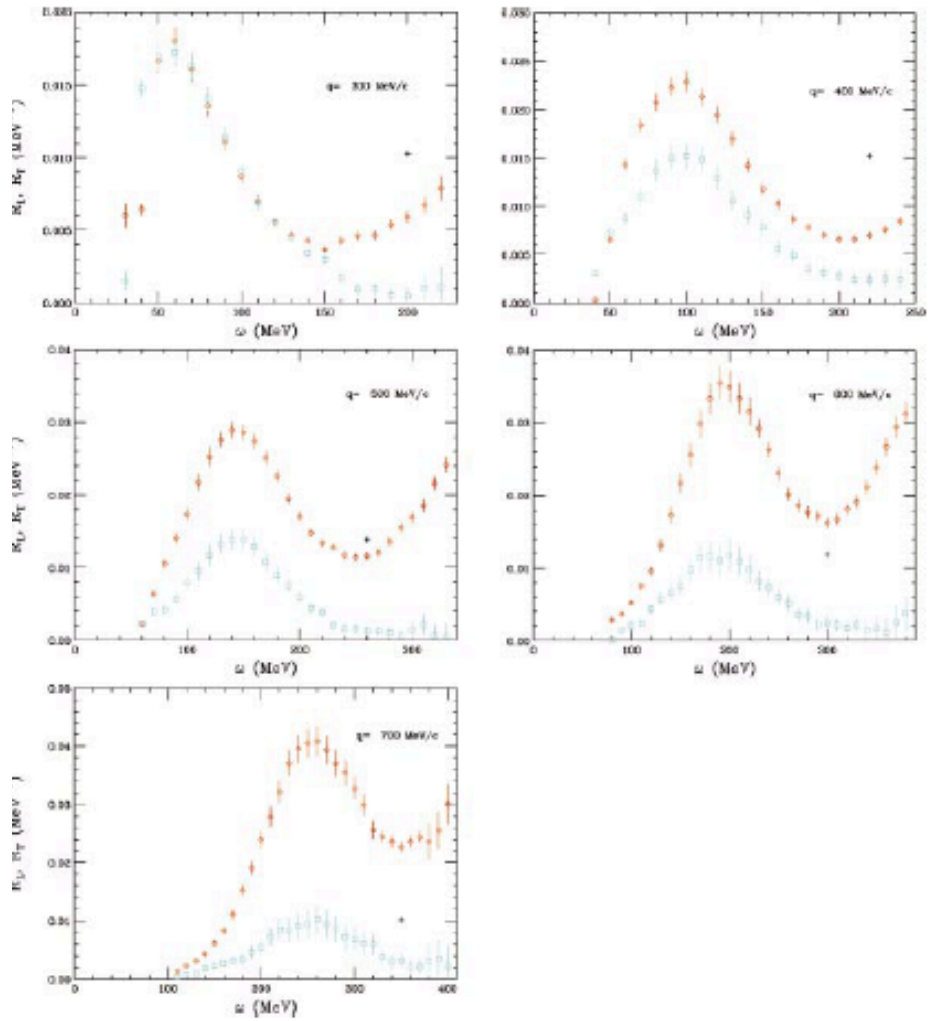
$$G_T = \frac{Q^2}{2qm}\left(ZG_{Mp}^2 + NG_{Mn}^2\right)$$

Starting Point: Transforming the Data

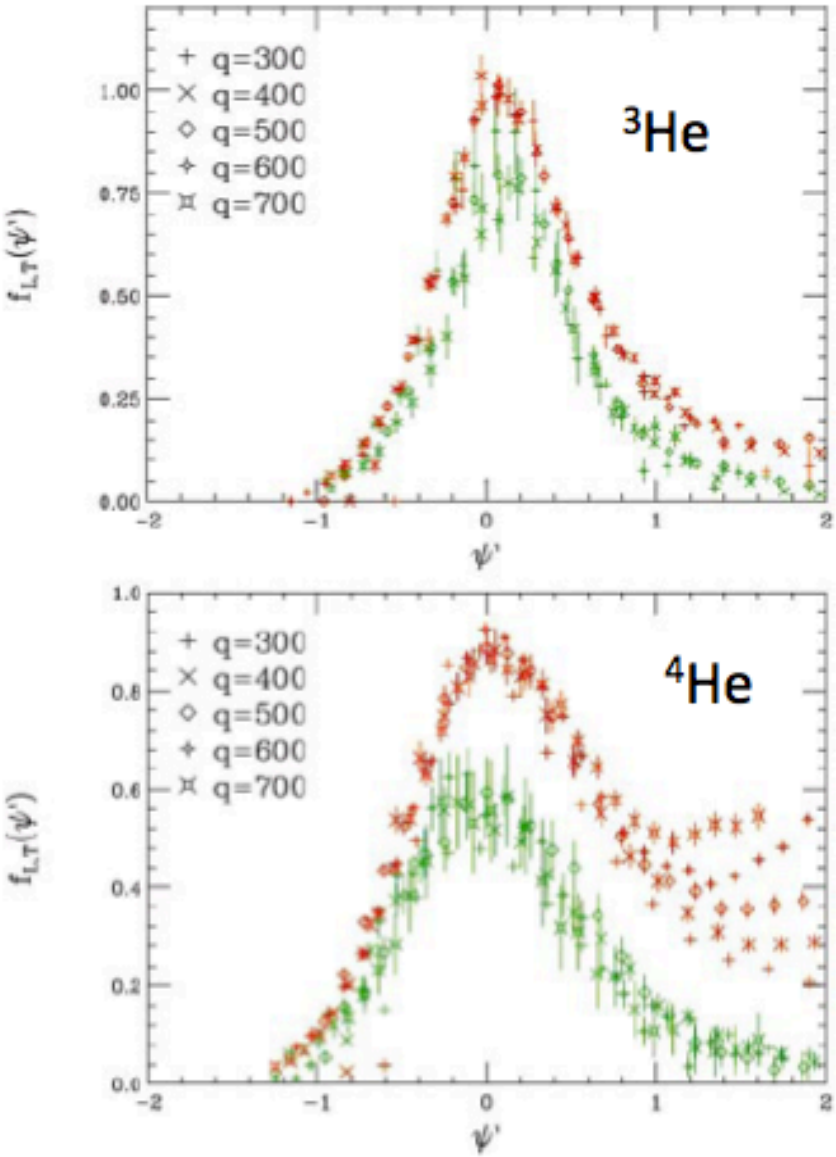
^{3}He



^{4}He



A possible origin of the MiniBooNE Effective M_A



The plots to the left show the longitudinal and transverse response for e + ^{3,4}He QE scattering as a function of the scaling variable ψ'.

$$\psi' = \frac{1}{k_F}\left(\sqrt{\omega^2 + 2m\omega} - q\right)$$

$$at\ \psi'=0\quad \omega=\sqrt{m^2+q^2} - m = T_N$$

Which is the energy transfer to a free nucleon at rest.

$$\psi' < 0, \omega < T_N \quad \psi' > 0, \omega > 0$$

Note large increase in the transverse response in going from ^{3}He to ^{4}He

This is all <u>vector</u> interactions

Euclidian Response Functions: PR C, 65, 024002 (cont.)

$$\tilde{E}(|\vec{q}|,\tau) = \int_{\omega_{th}}^{\infty} e^{-(\omega - E_0)\tau} R_{T,L}(|\vec{q}|,\omega) d\omega$$

$\tilde{E}(|\vec{q}|,\tau)$ can be calculated as follows

$$\tilde{E}_L(|\vec{q}|,\tau) = \langle 0 | \rho(\vec{q}) e^{-(H-E_0)\tau} \rho(\vec{q}) | 0 \rangle - e^{-\frac{q^2\tau}{2Am}} \langle 0(\vec{q}) | \rho(\vec{q}) | 0 \rangle$$

$$\tilde{E}_T(|\vec{q}|,\tau) = \langle 0 | \vec{j}_T(\vec{q}) e^{-(H-E_0)\tau} \vec{j}_T(\vec{q}) | 0 \rangle - e^{-\frac{q^2\tau}{2Am}} \langle 0(\vec{q}) | \vec{j}_T(\vec{q}) | 0 \rangle$$

$$E_{T,L}(q,\tau) = \frac{e^{\frac{q^2\tau}{2m}}}{(1+Q^2/\Lambda^2)^{-4}} \tilde{E}_{T,L}(q,\tau)$$

Is presented, removing the trivial kinetic energy dependence of the struck nucleon, and the Q^2 dependence of the nucleon FF

$R_{T,L}(|\vec{q}|,\omega)$: Standard response functions from experiment.

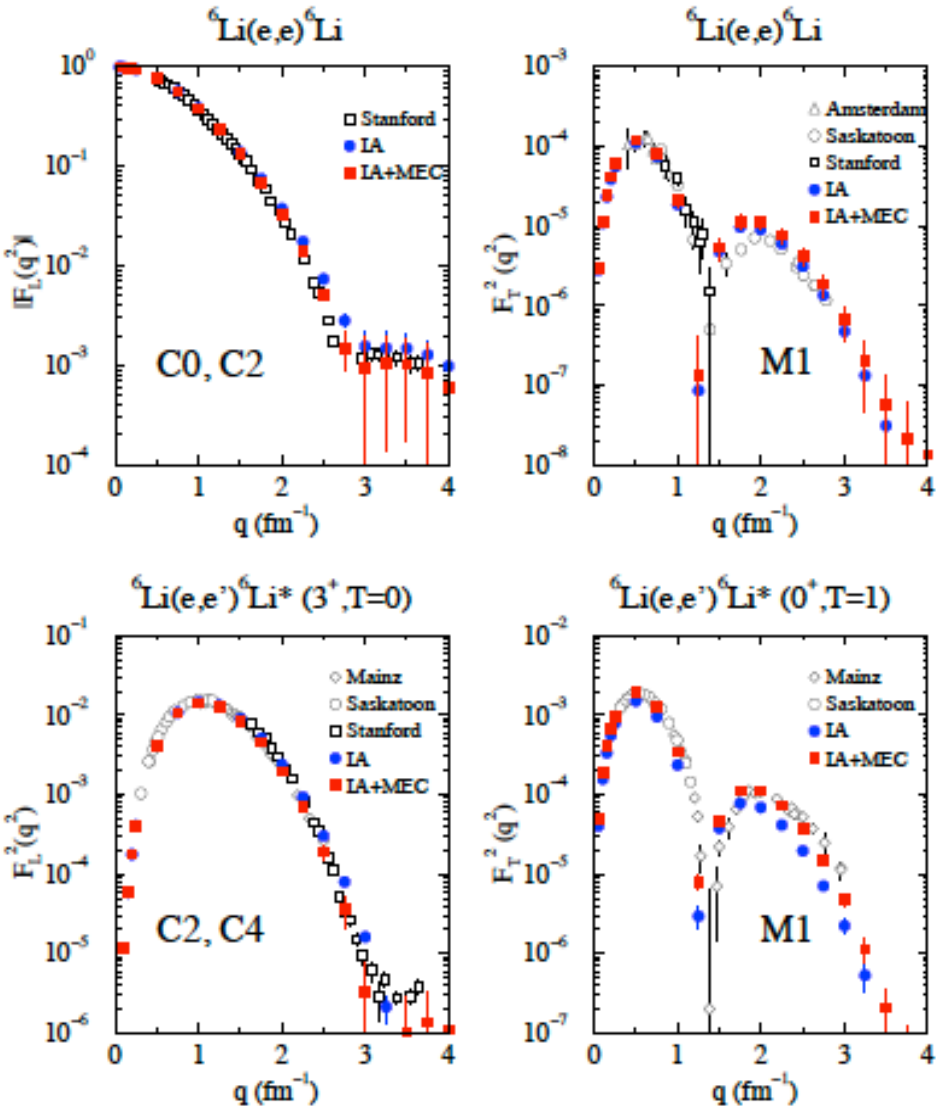
$|0\rangle$:Nuclear gs, $E=E_0$ calculated with realistic NN and NNN interactions

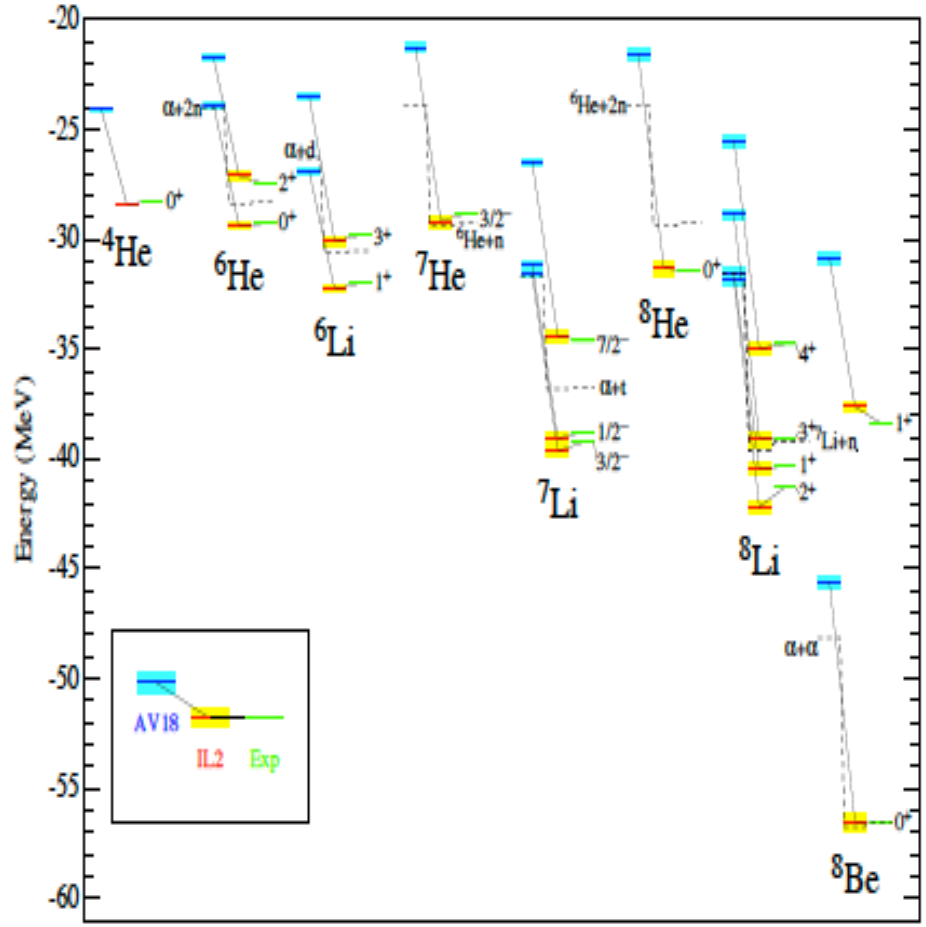
H: True Hamiltonian with same interactions as above

τ: units $(\text{MeV})^{-1}$, determines the energy interval of the response function

NOTE: The group doing these calculation are extremely successful in reproducing all the features of light nuclei; Masses, energy spectra, transition rates, etc. for A≤12.

Some of the Argonne/ Illinois GFMC Results for Light Nuclei





What are the EM Charge and Current Operators??

Covariant single nucleon vector current

$$j^{\mu} = \left\langle \bar{u}_N(p') \middle| F_1^N(Q^2)\gamma^{\mu} + F_2^N(Q^2)\frac{i\sigma^{\mu\nu}q_{\nu}}{2m} \middle| u_N(p) \right\rangle \qquad N = n, p$$

$$\rho_{i,NR}^{(1)}(\vec{q}) = \varepsilon_i e^{i\vec{q}\bullet\vec{r}} \quad \textit{negecting relatvistic corrections}$$

$$\vec{j}_i^{(1)}(\vec{q}) = \frac{\varepsilon_i}{2m}\{\vec{p}_i, e^{i\vec{q}\bullet\vec{r}}\} - \frac{i\mu_i^a}{2m}(\vec{q}_i \times \vec{\sigma}_i)e^{i\vec{q}\bullet\vec{r}}$$

Current Conservation requires:

$$\nabla\bullet\vec{j}(\vec{q}) = \frac{\partial\rho(\vec{q})}{\partial t}$$

$$\vec{q}\bullet\vec{j}(\vec{q}) = [H, \rho] \qquad H = \sum_i \frac{\vec{p}_i^{\,2}}{2m} + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk}$$

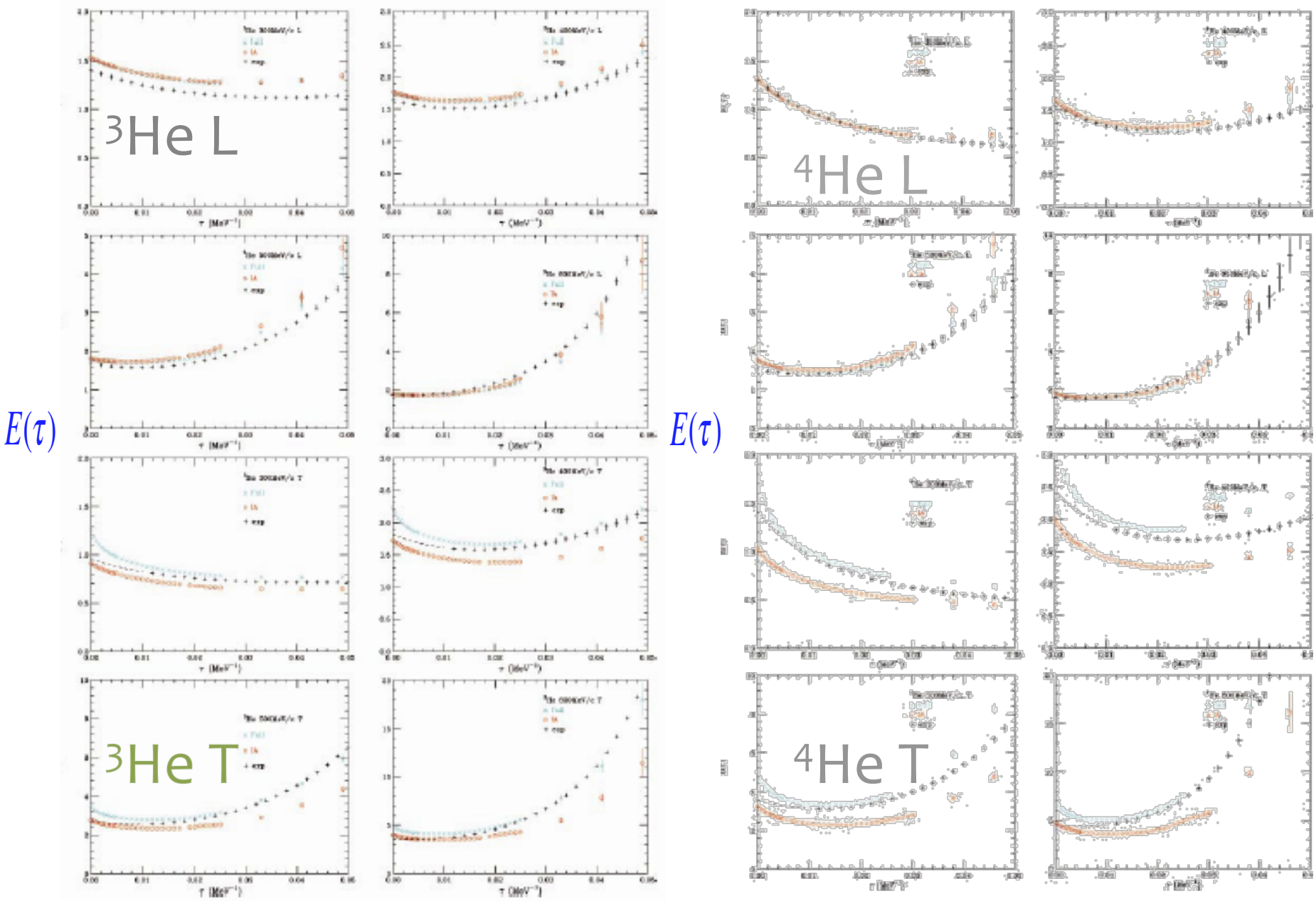
$$\vec{q}\bullet\vec{j}_i^{(1)}(\vec{q}) = [\frac{\vec{p}_i^{\,2}}{2m}, \rho_{i,NR}^{(1)}(\vec{q})]$$

$$\vec{q}\bullet\vec{j}_{ij}^{(2)}(\vec{q}) = [V_{ij}, \rho_{i,NR}^{(1)}(\vec{q}) + \rho_{j,NR}^{(1)}(\vec{q})]$$

<u>A 2-body current</u>

$$J = \sum_i j_i + \sum_{i<m} j_{i,m}$$

Results of Calculation, $\tilde{E}(\tau)$ for fixed q



How Big are these Effects Relative to Free Nucleons?

Sum Rule at fixed 3 momentum transfer *q*:

$$S_{T,L}(q) = \int_{\omega_{th}}^{\infty} S_{T,L}(q,\omega)d\omega = C_{T,L}\left[\langle 0|\tilde{O}^{*}_{T,L}(\vec{q})O_{T,L}(\vec{q})|0\rangle - |\langle 0|O_{T,L}(\vec{q})|0\rangle|^2\right]$$

$$C_T = \frac{2m^2}{Z\mu_p^2 + N\mu_n^2}, \quad C_L = \frac{1}{Z}$$

$$S_{T,L}(q) = C_{T,L}E_{T,L}(q,\tau=0)$$

TABLE I. Longitudinal sum rule obtained with one body only and with both one- and two-body charge operators.

	^{3}He		^{4}He		^{6}Li	
q (MeV/c)	1	1+2	1	1+2	1	1+2
300	0.787	0.763	0.670	0.649	0.977	0.933
400	0.921	0.875	0.859	0.815	0.995	0.932
500	0.964	0.901	0.941	0.881	0.990	0.921
600	0.982	0.908	0.973	0.910	0.990	0.924
700	0.994	0.914	0.994	0.942	0.994	0.938

TABLE II. Transverse sum rule obtained with one body only and with both one- and two-body current operators.

	^{3}He		^{4}He		^{6}Li	
q (MeV/c)	1	1+2	1	1+2	1	1+2
300	0.929	1.31	0.893	1.67	0.912	1.57
400	0.987	1.30	0.970	1.62	0.974	1.52
500	1.01	1.28	1.00	1.55	0.999	1.46
600	1.01	1.25	1.01	1.49	1.01	1.41
700	1.01	1.23	1.01	1.44	1.011	1.37

Further Info from PR C65 024002

Effect is due to n-p pairs

TABLE V. ^{4}He transverse sum rule: contribution of *pp* and *nn* pairs.

q (MeV/c)	1	1+2	1+2 *pp* or *nn* only
300	0.915	1.65	0.919
400	0.980	1.59	0.987
500	1.01	1.53	1.02
600	1.01	1.47	1.03
700	1.01	1.41	1.03

Small effect of 2-body currents evaluated in the Fermi Gas:

TABLE VII. Excess-strength contributions ΔS_L and ΔS_T to the Fermi-gas sum rules from terms involving two-nucleon currents.

q (MeV/c)	ΔS_L	ΔS_T
300	0.004	0.114
400	0.007	0.081
500	0.011	0.066
600	0.017	0.060
700	0.024	0.056

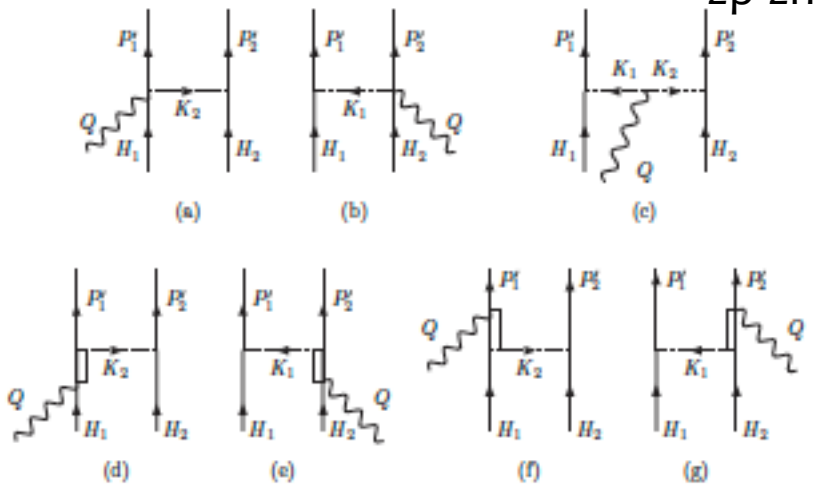
Some More Evidence

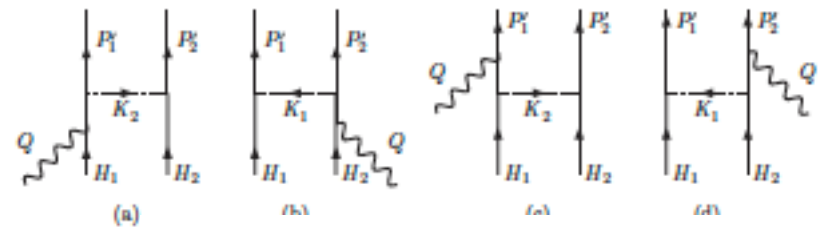
Amaro, et al, PHYSICAL REVIEW C **82, 044601 (2010)**

Meson Exchange Diags.

2p-2h fin. sts.

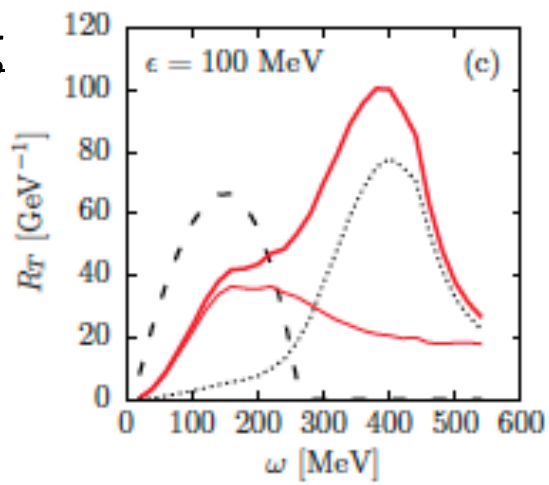
Correlation Diags.

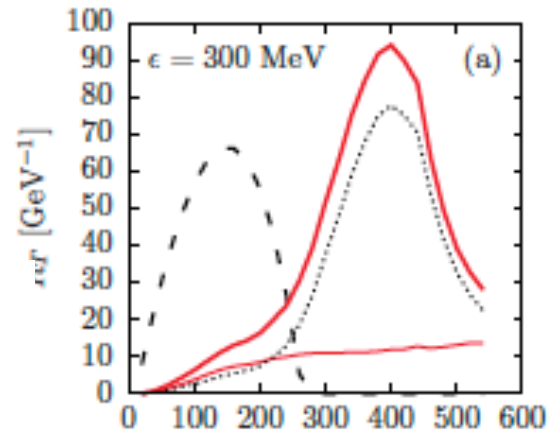


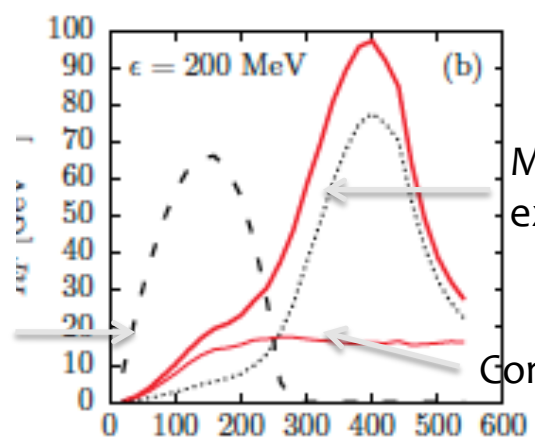


Electron Scattering

^{56}Fe, q=0.55GeV/c





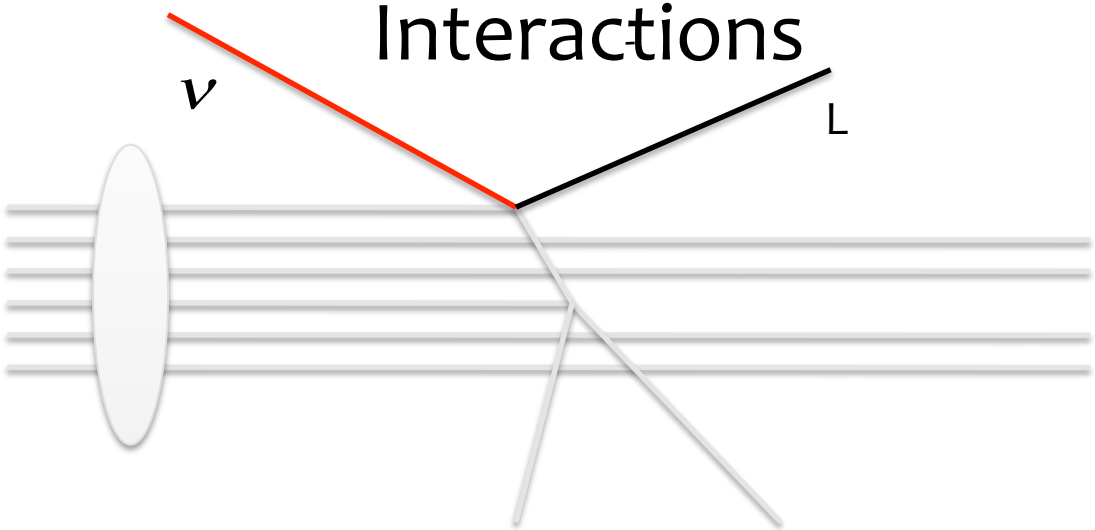


Meson exchange

One body RFG

Correlation

Final State Interactions



Mean Free Path

$$\lambda = \frac{1}{\sigma n} = \frac{1}{\sigma[A/(\frac{4\pi}{3}1.2^3 A)]} = \frac{7.24\bullet 10^{-39}}{40\bullet 10^{-27}} = 1.8\bullet 10^{-13} cm$$

Optical Model Att.

$$w(z) = w(0)e^{-\kappa z} \qquad \kappa = \frac{2mW}{\hbar p}$$

W = imaginary part of n-Nuc. optical potential

$$\kappa = \frac{2(.938)0.033}{0.2\bullet 0.5} = 0.619$$

p = external nucleon momentum

$$\langle z \rangle_{^{12}C} = \frac{3}{4} R_{^{12}C} = 2.06 f \qquad e^{-.619(2.06-1)} = 0.52$$

so 48% interact,

$$\langle z \rangle_{^{40}Ar} = \frac{3}{4} R_{^{40}Ar} = 3.08 f \qquad e^{-.619(3.08-1)} = 0.28$$

so 72% interact

Final State Interactions are Difficult to Treat

- Their study requires preparing well defined initial states in the nucleus
- Eg. Electron QE scattering on a nucleus with well defined q and ω
- Want to be able to see all final states due to FSI
- Using an optical model to characterize the FSI gives no information on the inelastic channels.
- Gets very complicated when dealing with interactions involved in SRC

Larry Weinstein at HENP and QCD Miami 2010

- Experiments eg. PRC 45 780(1992) (e,e'p) C,Al,Ni,Ta: $\langle E_p \rangle$ 180 MeV PRL 80, 5072 (1988), C.Fe. Au: E_p= 300-1800

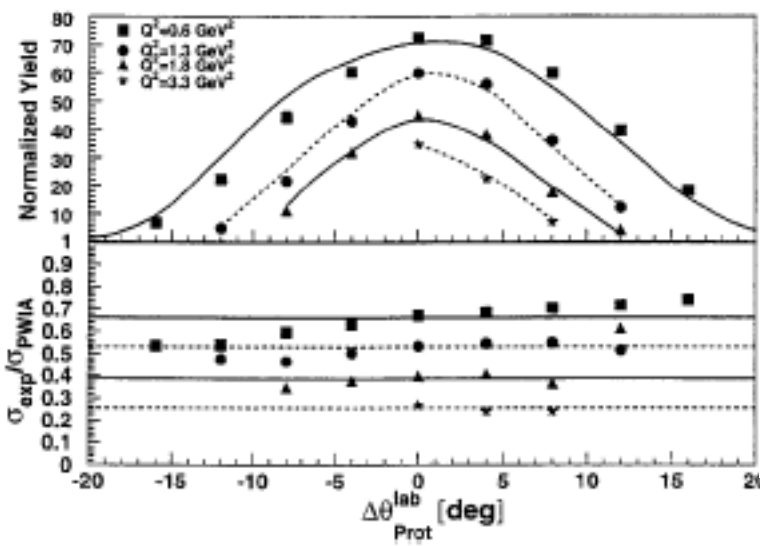


FIG. 2. (Upper panel) experimental $(e,e'p)$ coincidence yields vs the difference between the proton spectrometer lab angle and the conjugate angle for data from Fe at each momentum transfer. Scale factors of 0.21, 1.6, 2.25, and 35 have been applied at $Q^2 = 0.6$, 1.3, 1.8, and 3.3, respectively. (Lower panel) T_θ as a function of proton angle. The results are displaced by +0.2, +0.1, 0.0, and −0.15 for $Q^2 = 0.6$, 1.3, 1.8, and 3.3, respectively. In each case statistical errors of the data are smaller than the plotting symbols. The curves in each panel are simulations of the yield based on the model described in the text and normalized by a single T factor for each Q^2.

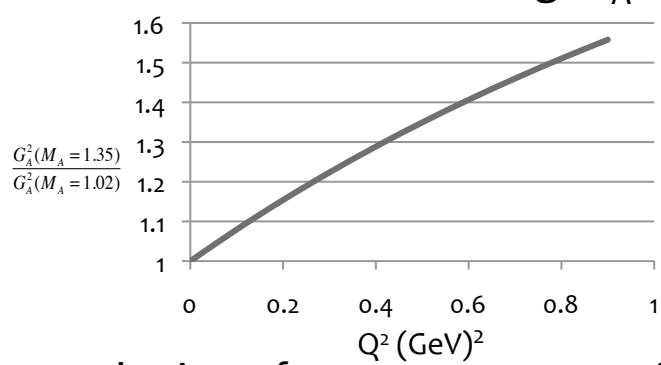
- FSI should be an element in the consideration in evaluating detector response. Smaller A is better.

Going Back to the Martini-Ericson RPA Presentation

- They neglect meson exchange currents, no real 2-body currents
- The approach likely contains and extends the correlation diagrams
- Both the magnetic and axial responses are increased by the same amount
- Thus the transverse yield can be written as follows

$$\left((G_M^2 \frac{\omega^2}{\vec{q}^2} + G_A^2)\left(\frac{Q^2}{\vec{q}^2} + 2\tan^2\frac{\theta}{2} \right) \pm 2G_M G_A \frac{k+k'}{M_N} \tan^2\frac{\theta}{2} \right) (R^{NN}_{\sigma\tau(T)} + 2R^{N\Delta}_{\sigma\tau(T)} + R^{\Delta\Delta}_{\sigma\tau(T)})$$

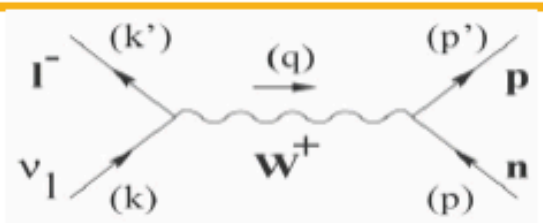
- Shows why the MiniBooNE fix of increasing M_A could fit neutrino and anti-neutrino data



- $\sigma(\nu) - \sigma(\bar{\nu})$ isolates the interference term, very important

Neutrino-nucleus cross-section

$$\mathcal{L}_W = \frac{G_F}{\sqrt{2}} \cos(\theta_C) l_\mu h^\mu$$



lepton

$$\langle k', s' | l_\mu | k, s \rangle = e^{-iqx} \bar{u}(k', s') \left[\gamma_\mu (1 - \gamma_5)\right] u(k, s)$$

$$\langle p', s' | h^\mu | p, s \rangle = e^{iqx} \bar{u}(p', s') \left[F_1(t)\gamma^\mu + F_2(t)\sigma^{\mu\nu} \frac{iq_\nu}{2M_N} + G_A(t)\gamma^\mu\gamma_5 + G_P(t)\gamma_5 \frac{q^\mu}{2M_N}\right] u(p, s)$$

hadron

$$t = q^2 = \omega^2 - \boldsymbol{q}^2$$

$$G_A(t) = g_A \left[1 - \frac{t}{M_A^2}\right]^{-2}$$

After non-relativistic reduction:

$$\frac{\partial^2 \sigma}{\partial \Omega \, \partial k'} = \frac{G_F^2 \cos^2\theta_c \, (\boldsymbol{k}')^2}{2\,\pi^2} \cos^2\frac{\theta}{2} \Bigg[G_E^2 \left(\frac{q_\mu^2}{\boldsymbol{q}^2}\right)^2 R_\tau^{NN}$$

charge nuclear response

$$+ \; G_A^2 \frac{(M_\Delta - M_N)^2}{2\,\boldsymbol{q}^2} R_{\sigma\tau(L)}^{N\Delta} + G_A^2 \frac{(M_\Delta - M_N)^2}{\boldsymbol{q}^2} R_{\sigma\tau(L)}^{\Delta\Delta}$$

isospin spin-longitudinal

$$+ \left(G_M^2 \frac{\omega^2}{\boldsymbol{q}^2} + G_A^2\right) \left(-\frac{q_\mu^2}{\boldsymbol{q}^2} + 2\tan^2\frac{\theta}{2}\right) \left(R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}\right)$$

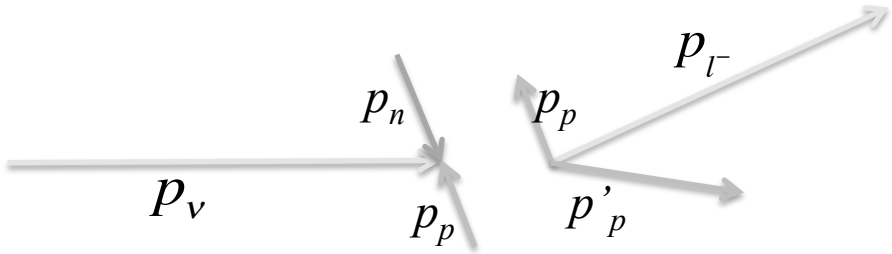
isospin spin-transverse

$$\begin{cases} + & (\nu) \\ - & (\bar{\nu}) \end{cases} \pm \; 2\,G_A\,G_M \frac{k + k'}{M_N} \tan^2\frac{\theta}{2} \left(R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}\right) \Bigg]$$

interference V-A

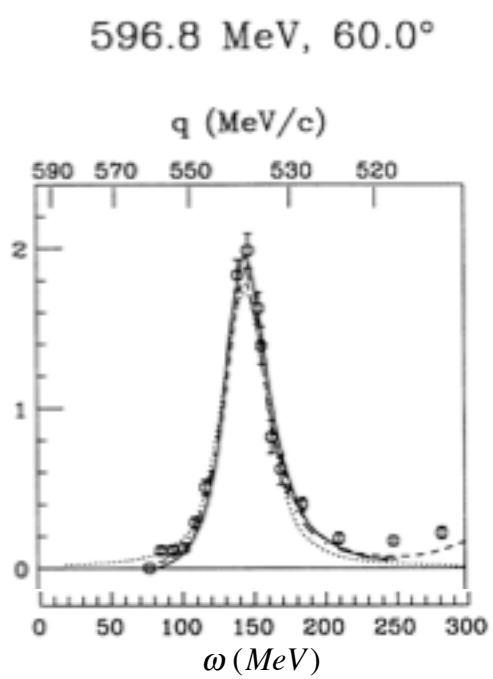
Absolute Normalization of the Flux $\nu_l + d \rightarrow l^- + 2p$

In d the rms separation of the nucleons is 4 fm

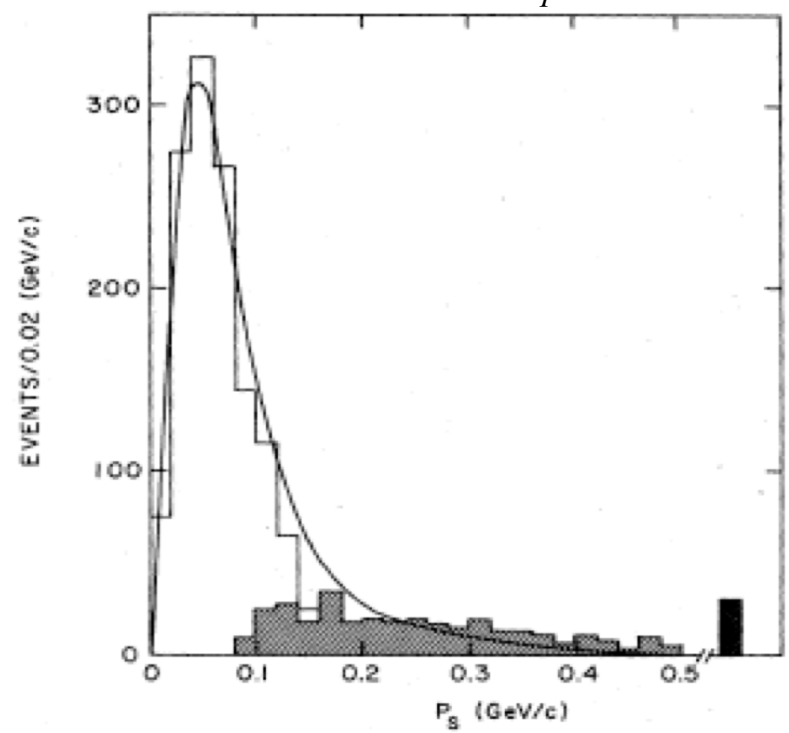


$$p_\nu - p_{l^-} = (\omega, \vec{q}) = p'_p - p_n = p'_p + p$$

e+d inclusive scattering



Spectator proton (p_p) spectrum



With ω and E_μ known, E_ν is determined!!
With q and ω known, $y=(\omega+2m\omega)^{.5} - q < 0$ can be selected.

Absolute Normalization of the Flux $\nu_l + d \rightarrow l^- + 2p$

- $\nu_l + d \rightarrow l^- + 2p$ best done in LD bubble chamber
- Likely impractical on this day and age
- What about D_2O-H_2O? How well can it be done?

  1.9x 10^4 QE /10^{20} pot QE rate per ton of water at 670m 120 GeV proton beam, 250kA horn current, and a 2m radius 280m long decay region.
- Rate likely not the problem
- Absolute Cross Section calculable to ~ 5%, perhaps better restricting to y<0.

Conclusions

- Neutrino-nucleus CCQE scattering is important but difficult to characterize and calculate
- Experimentalists must more careful to specify what they mean by QE.
- Measured Cross Sections are essential- Should know the flux!
- Determining the incident neutrino energy event by event in an issue.
- Enhancements to QE scattering seen in electron-nucleus scattering are essential to incorporate into neutrino-nucleus QE scattering
- Final state interactions really mess things up. In characterizing detector response the neutrino-nucleus interaction should be a primary concern.
- Differences between neutrino and anti-neutrino cross sections (yields) should be better understood before CP violation experiments are undertaken