NuSTEC Neutrino Generator School

Lecture T5

Quasielastic neutrino scattering

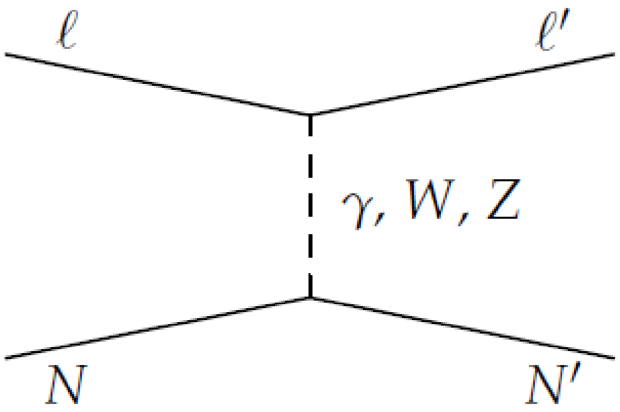
Luis Alvarez Ruso

Outline

- QE scattering on the nucleon
  - Structure of the electroweak current
  - Analysis of the CCQE and NCE cross sections
- (Some) many-body theory
  - Nucleon propagator in the medium. Spectral functions
  - Polarization propagators and nuclear response
- QE(-like) scattering
- RPA

QE scattering on the nucleon

$$\begin{aligned}
\text{EM}: \; l^{\pm}(k) + N(p) &\rightarrow l^{\pm}(k') + N(p') \\
\text{CC}: \; \nu(k) + n(p) &\rightarrow l^{-}(k') + p(p') \\
\bar{\nu}(k) + p(p) &\rightarrow l^{+}(k') + n(p') \\
\text{NC}: \; \nu(k) + N(p) &\rightarrow \nu(k') + N(p') \\
\bar{\nu}(k) + N(p) &\rightarrow \bar{\nu}(k') + N(p')
\end{aligned}$$



- Cross section:

$$\frac{d\sigma}{dk_0' d\Omega(\vec{k}')} = \frac{G_F^2}{(2\pi)^2} \frac{|\vec{k}'|}{k_0} L_{\mu\nu} W^{\mu\nu}$$

$$W^{\mu\nu} = \frac{1}{2M} \int \frac{d^3p'}{2E'} \delta^4(k' + p' - k - p) H^{\nu\mu}$$

$$H^{\alpha\beta} = \mathrm{Tr}\left[(\not{p} + M)\, \gamma^0\, (\Gamma^\alpha)^\dagger\, \gamma^0\, (\not{p}' + M)\, \Gamma^\beta \right]$$

$$\langle N' | \, J^\mu \, | N \rangle = \bar{u}(p') \Gamma^\mu u(p) = \mathcal{V}^\mu - \mathcal{A}^\mu$$

Electroweak nucleon current

$$\langle N'| J^\mu |N\rangle = \bar{u}(p')\Gamma^\mu u(p) = \mathcal{V}^\mu - \mathcal{A}^\mu$$

$$\mathcal{V}^\mu = \bar{u}(p')\left[\gamma^\mu F_1 + \frac{i}{2M}\sigma^{\mu\nu}q_\nu F_2 + \frac{q^\mu}{M}F_S\right]u(p)$$

$$\mathcal{A}^\mu = \bar{u}(p')\left[\gamma^\mu\gamma_5 F_A + \frac{i}{2M}\sigma^{\mu\nu}q_\nu\gamma_5 F_T + \frac{q^\mu}{M}\gamma_5 F_P\right]u(p)$$

- T-inv. $\Rightarrow F_i \in$ Reals
- T-inv. + C-sym. $\Rightarrow F_S = F_T = 0 \Leftrightarrow$ absence of 2nd class currents
- $F_i = F_i\,(q^2) \Leftrightarrow 2\,p{\cdot}q + q^2 = 0$

Electroweak nucleon current

$$\mathcal{V}^\mu = \bar{u}(p') \left[\gamma^\mu F_1 + \frac{i}{2M} \sigma^{\mu\nu} q_\nu F_2 \right] u(p)$$

$$\mathcal{A}^\mu = \bar{u}(p') \left[\gamma^\mu \gamma_5 F_A + \frac{q^\mu}{M} \gamma_5 F_P \right] u(p)$$

- Sachs form factors: $G_E = F_1 + \frac{q^2}{2m_N} F_2$

$$G_M = F_1 + F_2$$

- In the Breit frame: $\vec{p} = -\vec{q}/2, \; \vec{p'} = \vec{q}/2, \; q^2 = -\vec{q}^2$

$$\langle N'_{s'} | \mathcal{V}^0 | N_s \rangle = G_E(\vec{q}^2) \delta_{ss'}$$

$$\langle N'_{s'} | \vec{\mathcal{V}} | N_s \rangle = G_M(\vec{q}^2) i \chi_{s'} (\vec{\sigma} \times \vec{q}) \chi_s$$

$$\langle N'_{s'} | \mathcal{A}^0 | N_s \rangle = 0$$

$$\langle N'_{s'} | \vec{\mathcal{A}} | N_s \rangle = F_A(\vec{q}^2)(E+M) \left[\vec{\sigma} - \frac{(\vec{\sigma} \cdot \vec{q}) \vec{\sigma} (\vec{\sigma} \cdot \vec{q})}{(E+M)^2} \right] + F_P(\vec{q}^2) \vec{q} \frac{(\vec{\sigma} \cdot \vec{q})}{M}$$

Electroweak nucleon current

- Vector and EM form factors:

$V_a^\alpha = \mathcal{V}^\alpha \frac{\tau_a}{2}$ ← isovector current $V_Y^\alpha = \mathcal{V}_Y^\alpha I$ ← hypercharge (isoscalar) current

$$\langle p| V_{\mathrm{EM}}^\alpha |p\rangle = \langle p| V_3^\alpha + \frac{1}{2} V_Y^\alpha |p\rangle = \frac{\mathcal{V}^\alpha + \mathcal{V}_Y^\alpha}{2} \equiv \mathcal{V}_p^\alpha$$

$$\langle n| V_{\mathrm{EM}}^\alpha |n\rangle = \langle n| V_3^\alpha + \frac{1}{2} V_Y^\alpha |n\rangle = \frac{-\mathcal{V}^\alpha + \mathcal{V}_Y^\alpha}{2} \equiv \mathcal{V}_n^\alpha$$

Then: $\langle p| V_{\mathrm{CC}}^\alpha |n\rangle = \langle p| V_1^\alpha + i V_2^\alpha |n\rangle = \mathcal{V}^\alpha = \mathcal{V}_p^\alpha - \mathcal{V}_n^\alpha$

$$\begin{aligned}\langle p| V_{\mathrm{NC}}^\alpha |p\rangle &= \langle p| (1 - 2\sin^2\theta_W) V_3^\alpha - \sin^2\theta_W V_Y^\alpha |p\rangle \\ &= \left(\frac{1}{2} - \sin^2\theta_W\right) \mathcal{V}^\alpha + \sin^2\theta_W \mathcal{V}_Y^\alpha \\ &= \left(\frac{1}{2} - 2\sin^2\theta_W\right) \mathcal{V}_p^\alpha - \mathcal{V}_n^\alpha\end{aligned}$$

- Vector CC and NC form factors can be expressed in terms of EM ones

Electroweak nucleon current

- PCAC: The axial current in conserved in the chiral (m $\to$ 0) limit
- Consequences:

$$F_P(Q^2) = \frac{2M^2}{Q^2 + m_\pi^2} F_A(Q^2)$$

$$F_A(0) \equiv g_A = 2g_{NN\pi}$$ $\leftarrow$ Goldberger-Treiman relation

$$\mathcal{L}_{NN\pi} = -\frac{g_{NN\pi}}{f_\pi} \bar{N} \gamma_\mu \gamma_5 (\partial^\mu \vec{\pi}) \vec{\tau} N$$

QE scattering on the nucleon

- Cross section:
  - As an expansion in small variables $q^2, m_l^2 \ll M^2, E_\nu^2$

$$\frac{d\sigma}{dq^2} = \frac{1}{2\pi} G^2 c_{\rm EW}^2 \left[R - \frac{m_l^2}{4E_\nu^2} S + \frac{q^2}{4E_\nu^2} T \right] + \mathcal{O}(q^4, m_l^4, m_l^2 q^2)$$

  - CC: $c_{\rm CC} = \cos\theta_C$

$$\begin{aligned} R_{\rm CC} &= 1 + g_A^2 \\ S_{\rm CC} &= \frac{2E_\nu + M}{M} + g_A^2 \frac{2E_\nu - M}{M} \\ T_{\rm CC} &= 1 - g_A^2 + 2\frac{E_\nu}{M}(1 \mp g_A)^2 \mp 4\frac{E_\nu}{M} g_A \kappa^{\rm V} - \left(\frac{E_\nu}{M}\kappa^{\rm V}\right)^2 \\ &+ 4E_\nu^2 \left[\frac{1}{3}\left(\langle r_p^2 \rangle - \langle r_n^2 \rangle + g_A^2 \langle r_A^2 \rangle\right) - \frac{1}{2M^2}\kappa^{\rm V} \right] \end{aligned}$$

$$\kappa^{\rm V} = \mu_p - \mu_n - 1$$

QE scattering on the nucleon

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  - CC: $c_{\mathrm{CC}} = \cos\theta_C$
  - Large fraction of the CCQE cross section depends on a small number of nucleon properties
    - Charges, magnetic moments, mean squared radii

$$\langle r_p^2 \rangle = \frac{6}{G_{\mathrm{E}}^{(p)}(0)} \left. \frac{dG_{\mathrm{E}}^{(p)}(q^2)}{dq^2} \right|_{q^2=0}, \qquad \langle r_n^2 \rangle = 6 \left. \frac{dG_{\mathrm{E}}^{(n)}(q^2)}{dq^2} \right|_{q^2=0}$$

    - axial coupling and axial radius

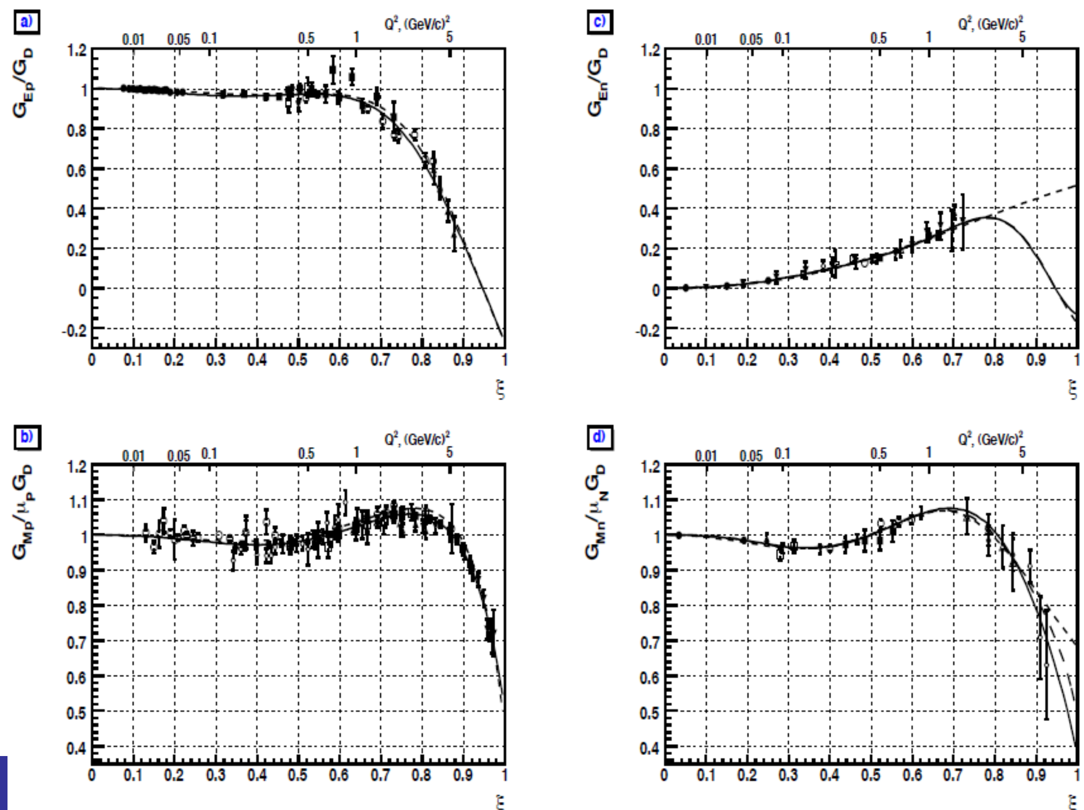
$$\langle r_A^2 \rangle = \frac{6}{F_A(0)} \left. \frac{dF_A(q^2)}{dq^2} \right|_{q^2=0}$$

ν QE scattering on the nucleon

- Measurement of the axial radius:
  - CCQE on H and D (BNL, ANL)

$$F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2} \qquad \langle r_A^2 \rangle = \frac{12}{{M_A}^2}$$

- M_A = 1.016 $\pm$ 0.026 GeV   Bodek et al., EPJC 53 (2008)
- Using:



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    - M_A= 1.016 $\pm$ 0.026 GeV Bodek et al., EPJC 53 (2008)

  - From π electroproduction on p:

$$6 \left. \frac{dE_{0+}^{(-)}}{dq^2} \right|_{q^2=0} = \langle r_A^2 \rangle + \frac{3}{M} \left(\kappa^{\mathrm{V}} + \frac{1}{2} \right) + \frac{3}{64 f_\pi^2} \left(1 - \frac{12}{\pi^2} \right)$$

    - M_A= 1.014 $\pm$ 0.016 GeV Liesenfeld et al., PLB 468 (1999) 20

QE scattering on the nucleon

- Cross section:
  - As an expansion in small variables $q^2, m_l^2 \ll M^2, E_\nu^2$

$$\frac{d\sigma}{dq^2} = \frac{1}{2\pi} G^2 c_{\rm EW}^2 \left[R - \frac{m_l^2}{4E_\nu^2} S + \frac{q^2}{4E_\nu^2} T \right] + \mathcal{O}(q^4, m_l^4, m_l^2 q^2)$$

  - NC: $c_{\rm NC} = 1/4$

$$R_{\rm NC}^{(p)} = \alpha_{\rm V}^2 + (g_A - \Delta s)^2$$

$$T_{\rm NC}^{(p)} = \alpha_{\rm V}^2 - (g_A - \Delta s)^2 + 2\frac{E_\nu}{M}\left[\alpha_{\rm V} \mp (g_A - \Delta s)\right]^2 \mp 4\frac{E_\nu}{M}(g_A - \Delta s)\kappa_{\rm NC}^{(p)} - \left(\frac{E_\nu}{M}\kappa_{\rm NC}^{(p)}\right)^2$$
$$+ \; 4E_\nu^2 \left\{ \alpha_{\rm V} \left[\frac{1}{3}\left(\alpha_{\rm V}\langle r_p^2\rangle - \langle r_n^2\rangle - \langle r_s^2\rangle\right) - \frac{1}{2M^2}\kappa_{\rm NC}^{(p)} \right] + \frac{1}{3}(g_A - \Delta s)\left(g_A\langle r_A^2\rangle - \Delta s\langle r_{As}^2\rangle\right) \right\}$$

$$R_{\rm NC}^{(n)} = 1 + (g_A + \Delta s)^2$$

$$T_{\rm NC}^{(n)} = 1 - (g_A + \Delta s)^2 + 2\frac{E_\nu}{M}\left[1 \mp (g_A + \Delta s)\right]^2 \pm 4\frac{E_\nu}{M}(g_A + \Delta s)\kappa_{\rm NC}^{(n)} - \left(\frac{E_\nu}{M}\kappa_{\rm NC}^{(n)}\right)^2$$
$$+ \; 4E_\nu^2 \left\{ -\frac{1}{3}\left(\alpha_{\rm V}\langle r_n^2\rangle - \langle r_p^2\rangle - \langle r_s^2\rangle\right) + \frac{1}{2M^2}\kappa_{\rm NC}^{(n)} + \frac{1}{3}(g_A + \Delta s)\left(g_A\langle r_A^2\rangle + \Delta s\langle r_{As}^2\rangle\right) \right\}$$

$$\kappa_{\rm NC}^{(p)} = \alpha_{\rm V}(\mu_p - 1) - \mu_n - \mu_s \qquad \kappa_{\rm NC}^{(n)} = 1 - \mu_p + \alpha_{\rm V}\mu_n - \mu_s \qquad \alpha_{\rm V} = 1 - 4\sin^2\theta_W$$

QE scattering on the nucleon

- Strangeness content of the nucleon:
  - $\langle r_s^2 \rangle$, μ_s, $\langle r_{As}^2 \rangle$ $\leftarrow$ insignificant
  - Δs strange axial coupling $\Leftrightarrow$ strange quark contribution to the spin

$$\left. \frac{d\sigma_{\rm NC}^{(p)}/dq^2}{d\sigma_{\rm NC}^{(n)}/dq^2} \right|_{q^2=0} = \frac{\alpha_{\rm V}^2 + (g_A - \Delta s)^2}{1 + (g_A + \Delta s)^2} \approx \frac{(g_A - \Delta s)^2}{1 + (g_A + \Delta s)^2} \approx \begin{cases} 0.62 & \text{if } \Delta s = 0 \\ 1.27 & \text{if } \Delta s = -0.3 \end{cases}$$

  - A recent global fit: Pate, Trujillo, arXiv:1308.5694

Nucleon propagator in the medium

- Green's function:

$$iG(x,x') = \frac{\langle \phi_0 \left| T\left[\psi(x)\psi^\dagger(x')\right] \right| \phi_0 \rangle}{\langle \phi_0 | \phi_0 \rangle}$$

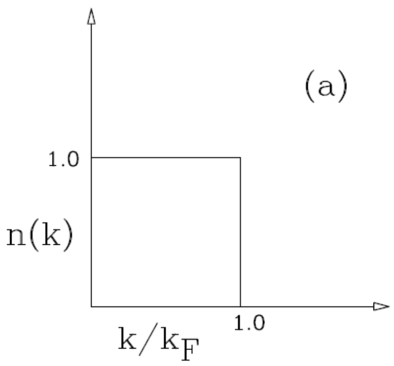
- $\phi_0 \leftarrow$ ground state of the system: $H|\phi_0\rangle = E|\phi_0\rangle$

- Free nucleon propagator in the medium
- ϕ_0 : system of non-interacting nucleons $\Leftrightarrow$ Fermi gas

$$\begin{aligned}
D(p) &= (\not{p} + M)G_0(p) \\
G_0(p) &= \frac{1}{p^2 - M^2 + i\epsilon} + 2\pi i \delta(p^2 - M^2)\theta(p^0) n(\vec{p}) \\
&= \frac{n(\vec{p})\theta(p^0)}{p^2 - M^2 - i\epsilon} + \frac{1 - n(\vec{p})\theta(p^0)}{p^2 - M^2 + i\epsilon} \\
&= \frac{1}{p^0 + E_p - i\epsilon}\left[\frac{n(\vec{p})}{p^0 - E_p - i\epsilon} + \frac{1 - n(\vec{p})}{p^0 - E_p + i\epsilon}\right]
\end{aligned}$$

hole particle

$$n(p) = \theta(p_F - p)$$



$$E_p = \sqrt{\vec{p}^2 + M^2}$$

Nucleon propagator in the medium

- Full nucleon propagator in the medium
- Selfenergy: $G = G_0 + G_0 \Sigma G_0$
- In terms of the proper selfenergy: $\Sigma = \Sigma_0 + \Sigma_0 G_0 \Sigma_0 + \ldots$
- Dyson equation:

$$
\begin{aligned}
G &= G_0 \Sigma_0 G_0 + G_0 \Sigma_0 G_0 \Sigma_0 G_0 + \ldots \\
&= G_0 + G_0 \Sigma_0 (G_0 + G_0 \Sigma_0 G_0 + \ldots) \\
G &= G_0 + G_0 \Sigma_0 G \\
G &= G_0 (1 - \Sigma_0 G_0)^{-1}
\end{aligned}
$$

- For particles and holes separately:

$$G_0 = \frac{1}{p^2 - M^2} \Rightarrow G = \frac{1}{p^2 - M^2 - \Sigma_0}$$

Σ_0 is calculated "perturbatively"

Spectral functions

- Full nucleon propagator in the medium
- Lehmann representation:

$$D(p) = (\not{p} + M)G(p)$$

$$G(p) = \frac{1}{p^0 + E_p - i\epsilon}\left[\int_{-\infty}^{\mu} \frac{\mathcal{A}_h(\omega,\vec{p})}{p^0 - \omega - i\epsilon} d\omega + \int_{\mu}^{\infty} \frac{\mathcal{A}_p(\omega,\vec{p})}{p^0 - \omega + i\epsilon} d\omega\right]$$

$$\mu^2 = \vec{p}_F^{\,2} + M^2 + \mathrm{Re}\Sigma(\mu, p_F)$$

$$\mathcal{A}_{p,h}(p) = \mp\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(p)}{[p^2 - M^2 - \mathrm{Re}\Sigma(p)]^2 + [\mathrm{Im}\Sigma(p)]^2}$$

- The hole (particle) spectral function $A_{h(p)}(p^0,\mathbf{p})$ represents the probability of removing (adding) a nucleon of momentum $|\mathbf{p}|$ changing the energy of the system by p^0
- Occupation number: $n(\vec{p}) = \int dp_0 (2p_0) \mathcal{A}_h(p^0, \vec{p})$

Spectral functions

- Full nucleon propagator in the medium
- Lehmann representation:

$$D(p) = (\not p + M) G(p)$$

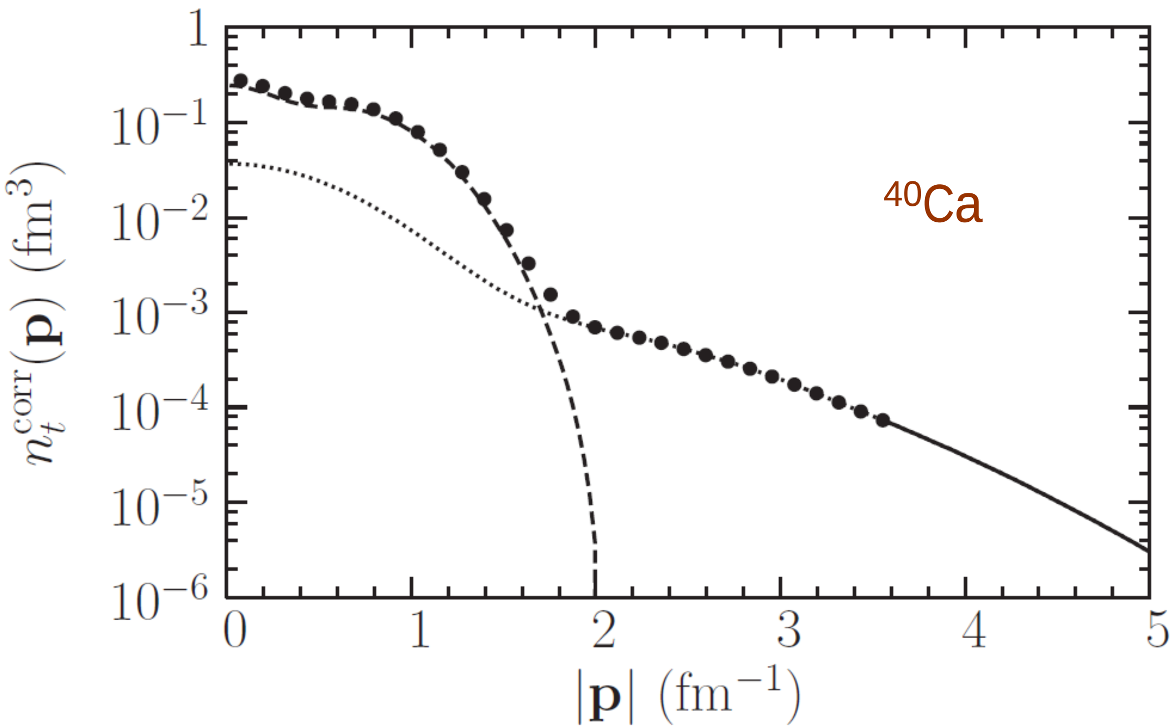
$$G(p) = \frac{1}{p^0 + E_p - i\epsilon} \left[\int_{-\infty}^{\mu} \frac{\mathcal{A}_h(\omega, \vec{p})}{p^0 - \omega - i\epsilon} d\omega + \int_{\mu}^{\infty} \frac{\mathcal{A}_p(\omega, \vec{p})}{p^0 - \omega + i\epsilon} d\omega \right]$$

$$\mathcal{A}_{p,h}(p) = \mp \frac{1}{\pi} \frac{\mathrm{Im}\Sigma(p)}{[p^2 - M^2 - \mathrm{Re}\Sigma(p)]^2 + [\mathrm{Im}\Sigma(p)]^2}$$

- $\Sigma \to 0$: G $\to$ G_0
- ImΣ = 0 $\Rightarrow$ mean-field approximation: $p^2 - M^2 - \mathrm{Re}\Sigma(p) = 0$
- In particular, if ReΣ = 2 M U + U^2: $p^0 = \sqrt{\vec{p}^2 + [M + U(p)]^2}$

Spectral functions

- Ingredients of a realistic hole spectral function:
  - Mean field part (80-90 %)
  - Correlated part (from NN interactions)

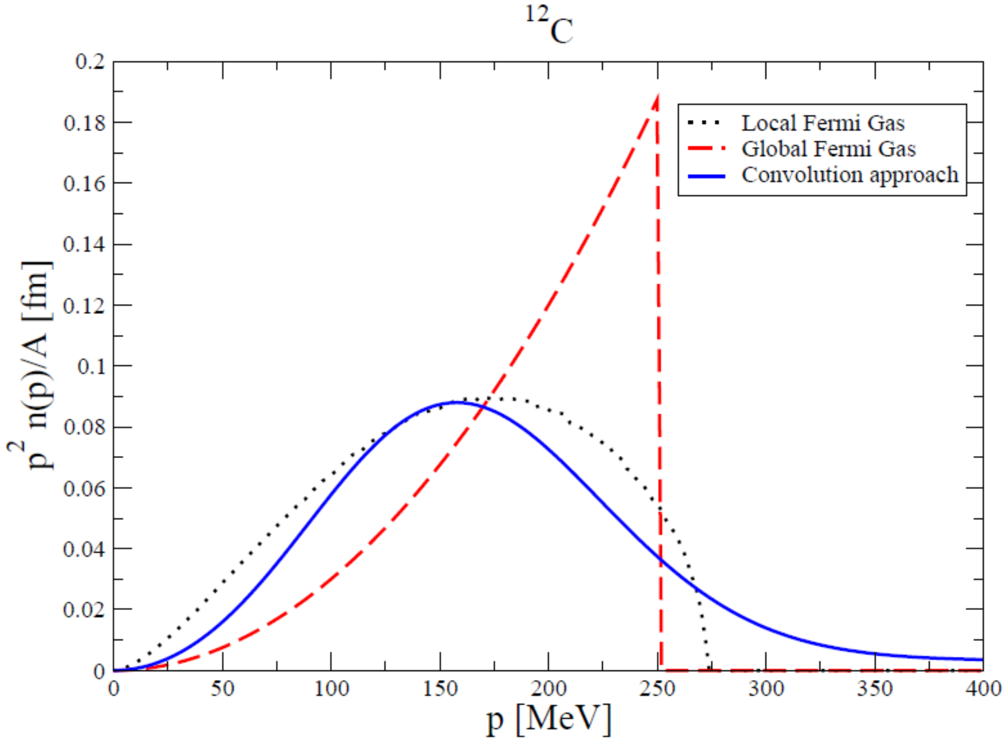


Ankowski, Sobczyk. PRC77(2008)

Spectral functions

- Ingredients of a realistic hole spectral function:
  - Mean field part (80-90 %)
  - Correlated part (from NN interactions)

- Local FG has a more realistic momentum distribution than Global FG



Spectral functions

- Particle spectral function:
  - Optical potential: $U = V - i\, W$
  - $V \sim 25$ MeV $\leftarrow$ fitted to p-A data
  - W: 1) $W = \sigma\, \rho\, v/2$

    2) Correlated Glauber approximation

    (straight trajectories, frozen spectators)

    Benhar et al., PRC 44 (1991) 2328

Polarization propagator

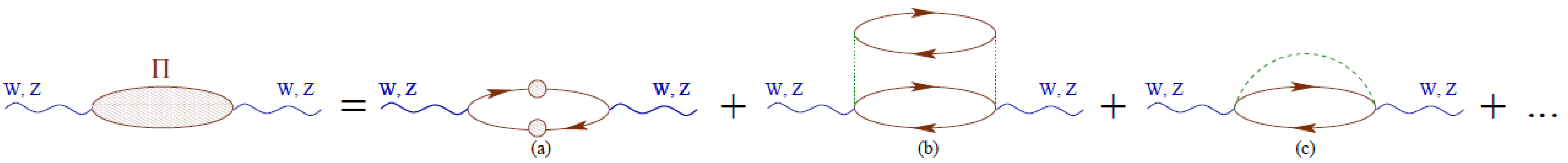
- Inclusive cross section per unit volume (well defined for an extended system)

$$\frac{d}{d^3r}\left(\frac{d\sigma}{dk_0' d\Omega(\vec{k}')}\right) = \frac{G_F^2}{(2\pi)^2}\frac{|\vec{k}'|}{k_0} L_{\mu\nu} W^{\mu\nu}$$

$$W^{\alpha\beta} = W_s^{\alpha\beta} + i W_a^{\alpha\beta}$$

- A classic result of many-body theory:

$$W^{\alpha\beta}_{(s,a)} = -\frac{1}{\pi}\,\mathrm{Im}\,\Pi^{\alpha\beta}_{(s,a)}$$



Polarization propagator

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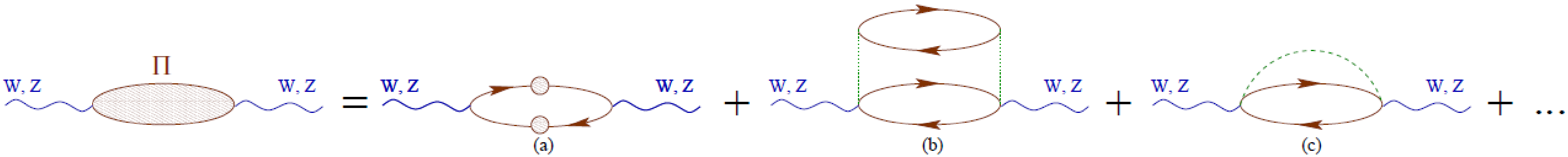
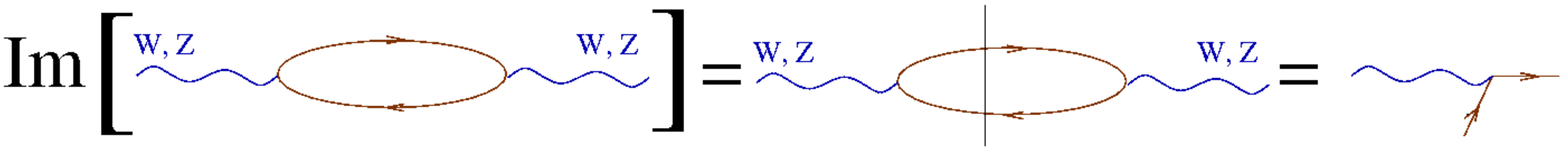
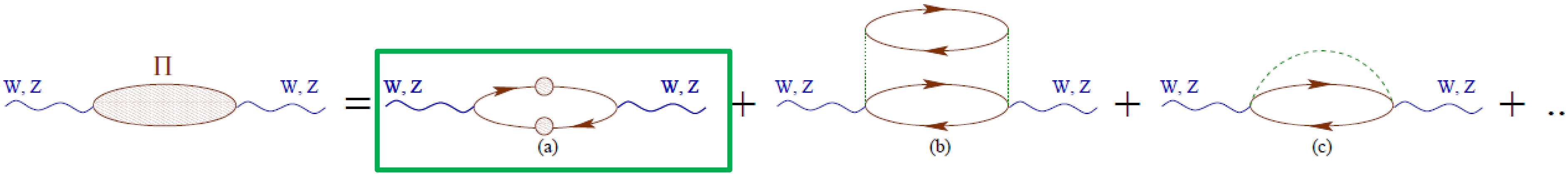


- Cutkosky rules:



Polarization propagator

$$W^{\alpha\beta}_{(s,a)} = -\frac{1}{\pi}\,\mathrm{Im}\,\Pi^{\alpha\beta}_{(s,a)}$$



$$\mathrm{Im}\,\Pi^{\alpha\beta}_{(s,a)} = -2\pi^2 \int \frac{d^4p}{(2\pi)^4} H^{\beta\alpha}_{(s,a)} \mathcal{A}_p(p+q)\,\mathcal{A}_h(p)$$

$$H^{\alpha\beta} = \mathrm{Tr}\left[(\not{p} + M)\,\gamma^0\,(\Gamma^\alpha)^\dagger\,\gamma^0\,(\not{p}' + M)\,\Gamma^\beta\right].$$

$$\Gamma^\mu = \gamma^\mu F_1 + \frac{i}{2M}\sigma^{\mu\nu}q_\nu F_2 - \gamma^\mu\gamma_5 F_A - \frac{q^\mu}{M}\gamma_5 F_P$$

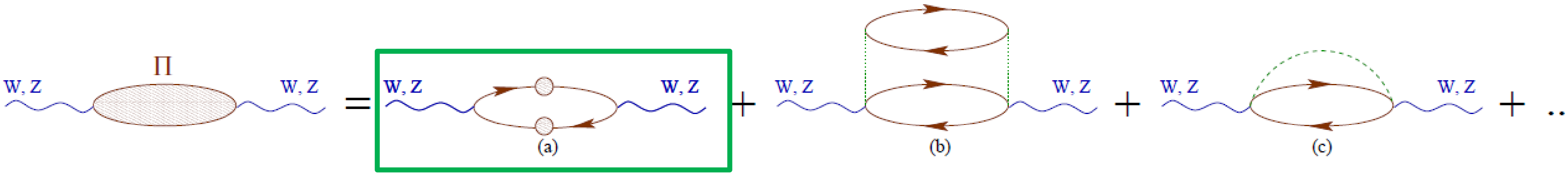
$$\mathcal{A}_{p,h}(p) = \mp\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(p)}{[p^2 - M^2 - \mathrm{Re}\Sigma(p)]^2 + [\mathrm{Im}\Sigma(p)]^2}$$

$\Sigma \to 0$ ⇒ Fermi gas model

Im$\Sigma \to 0$ ⇒ Mean field approximation

Polarization propagator

$$W^{\alpha\beta}_{(s,a)} = -\frac{1}{\pi}\,\mathrm{Im}\,\Pi^{\alpha\beta}_{(s,a)}$$



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$$H^{\alpha\beta} = \mathrm{Tr}\left[(\not{p} + M)\,\gamma^0\,(\Gamma^\alpha)^\dagger\,\gamma^0\,(\not{p}' + M)\,\Gamma^\beta \right] .$$

$$\Gamma^\mu = \gamma^\mu F_1 + \frac{i}{2M}\sigma^{\mu\nu} q_\nu F_2 - \gamma^\mu \gamma_5 F_A - \frac{q^\mu}{M}\gamma_5 F_P$$

$$\mathcal{A}_{p,h}(p) = \mp\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(p)}{[p^2 - M^2 - \mathrm{Re}\Sigma(p)]^2 + [\mathrm{Im}\Sigma(p)]^2}$$

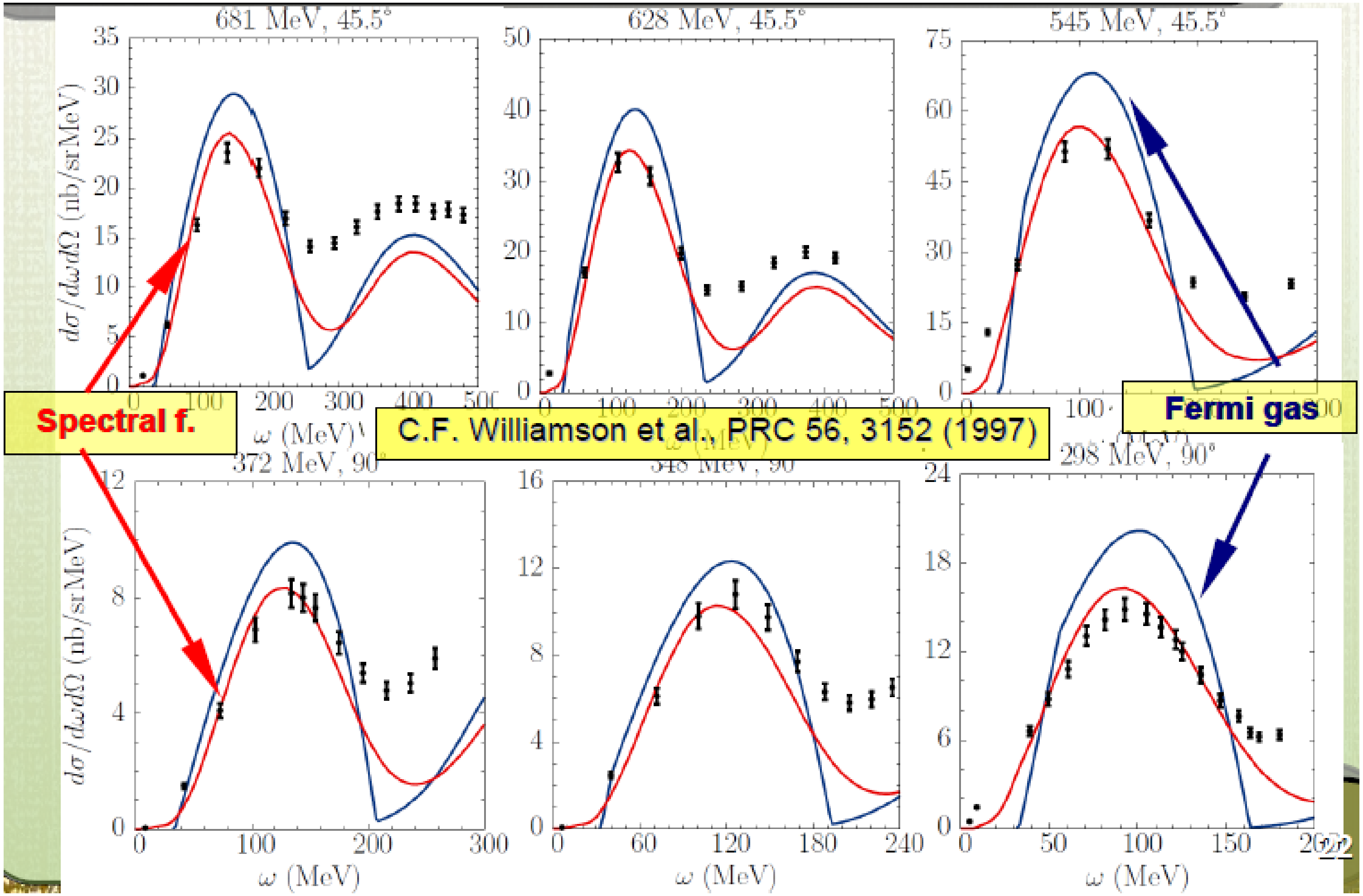
$$\mathrm{Im}\Sigma \to 0$$

$$\mathrm{Re}\Sigma = -2E_B\sqrt{\vec{p}^{\,2} + M^2} + E_B^2$$

$\Rightarrow$ Smith-Moniz Relativistic FG

EMQE

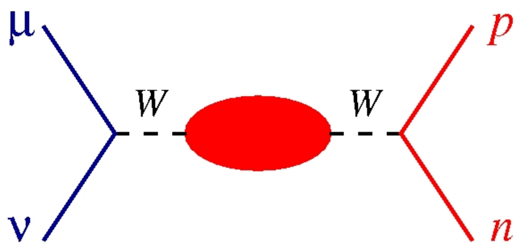
- Agreement with data considerably improved by p and h spectral functions



Ankowski, Sobczyk. PRC77(2008)

CCQE

- Long range RPA correlations



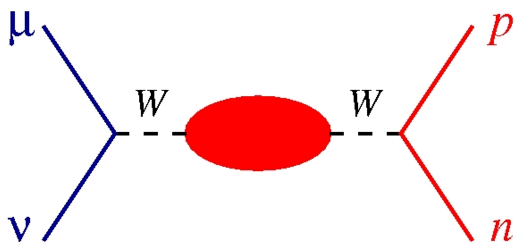
- RPA equation (schematically):

$$\Pi_{\mathrm{RPA}} = \Pi_0 + \Pi_0 V \Pi_{\mathrm{RPA}}$$

V=V(ρ) $\leftarrow$ effective, density dependent, NN interaction

CCQE

- Long range RPA correlations



- "Poor man" RPA (Oset et al.)
  - Π_0 calculated with the Local FG
  - Approximate resummation of the series
  - Applies to inclusive processes; not suitable for transitions to discrete states

But

CCQE

- Long range RPA correlations
- "Poor man" RPA (Oset et al.)
  - Π_0 calculated with the Local FG
  - Approximate resummation of the series
  - Applies to inclusive processes; not suitable for transitions to discrete states

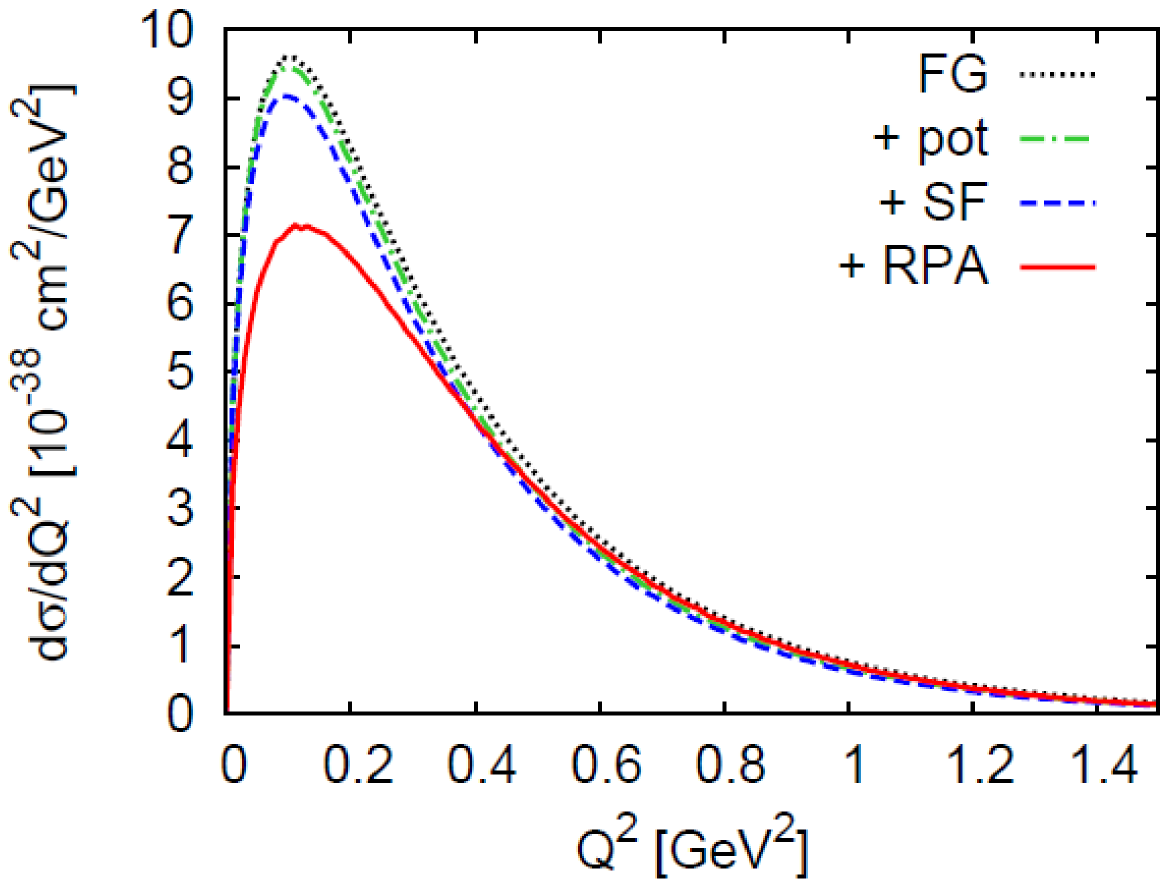
But

  - Incorporates explicitly π and ρ exchange and Δ-hole states
  - Has been successfully applied to π, γ and electro-nuclear reactions
  - Describes correctly μ capture on ^{12}C and LSND CCQE

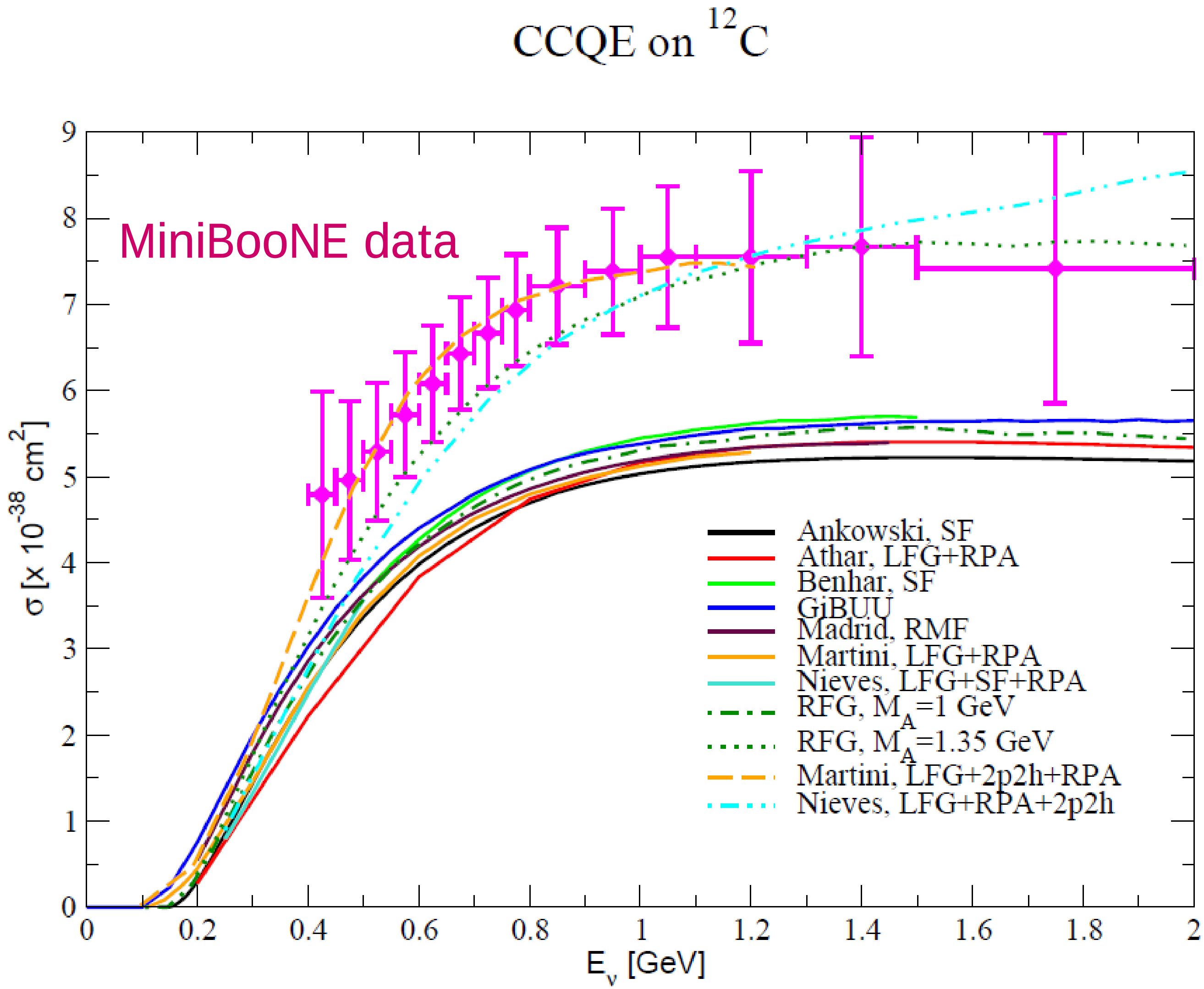
    Nieves et. al. PRC 70 (2004) 055503
  - Important at low Q^2 for CCQE at MiniBooNE energies

CCQE

- RPA long range correlations
  - CCQE on ^{12}C averaged over the MiniBooNE flux



CCQE



CCQE on 12C
MiniBooNE data
σ [x 10-38 cm2]
Eν [GeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
1
2
3
4
5
6
7
8
9
Ankowski, SF
Athar, LFG+RPA
Benhar, SF
GiBUU
Madrid, RMF
Martini, LFG+RPA
Nieves, LFG+SF+RPA
RFG, MA=1 GeV
RFG, MA=1.35 GeV
Martini, LFG+2p2h+RPA
Nieves, LFG+RPA+2p2h

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