Quasielastic Scattering at MiniBooNE Energies

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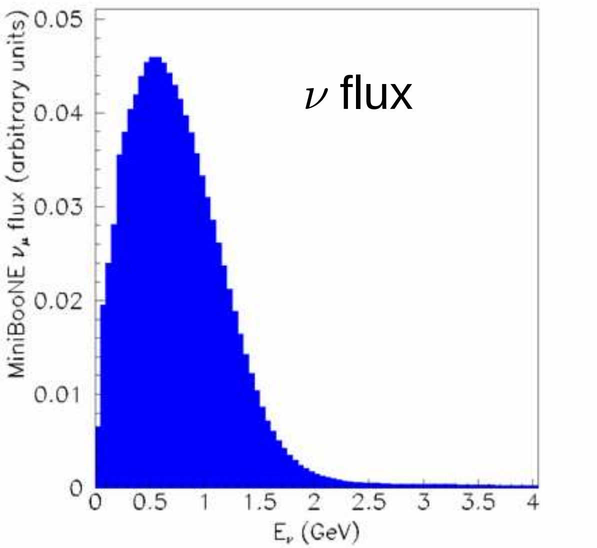
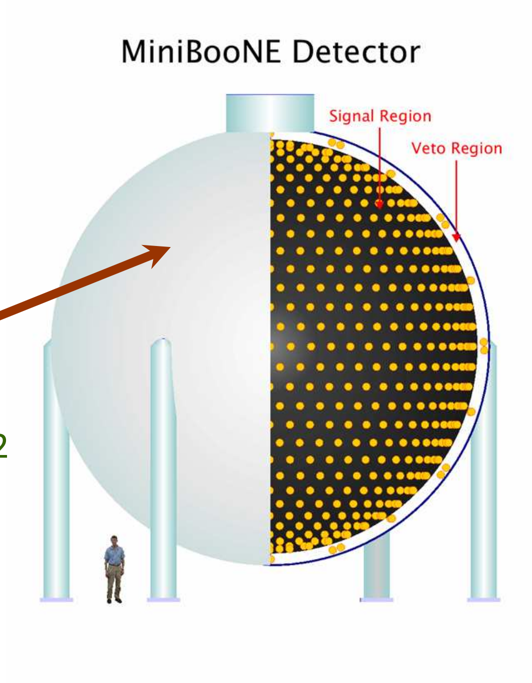
Introduction

- MiniBooNE has collected the largest sample of low energy ν_μ CCQE events to date. Aguilar-Arevalo et. al., PRL 100 (2008) 032301



$< E_\nu > \sim 750$ MeV

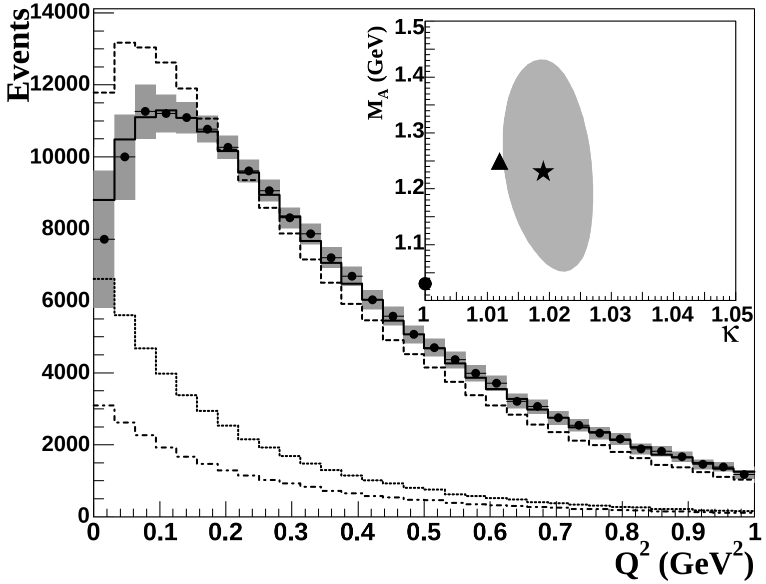
Mineral Oil: CH_2



- CCQE is relevant for oscillation experiments
- CCQE is interesting by itself:
  - Axial form factor of the nucleon (M_A)
  - Nuclear correlations

Introduction

- The shape of $\langle d\sigma/d\cos\theta_\mu dE_\mu\rangle$ is accurately described by a Global Fermi Gas Model Smith, Moniz, NPB 43 (1972) 605 with: E_B = 34 MeV, p_F = 220 MeV



But

- $$E_p^{\min} = \kappa\left(\sqrt{M^2+p_F^2}-\omega+E_B\right)\,,\quad \kappa = 1.019 \pm 0.011$$

- M_A = 1.23 $\pm$ 0.20 GeV
  consistent with M_A = 1.2 $\pm$ 0.12 GeV (K2K)
  higher than M_A = 1.01 $\pm$ 0.01 GeV ($\nu d\,,\bar{\nu}p\,,(e,e'\pi)$, BBBA07)
  M_A = 1.05 $\pm$ 0.08 GeV (mainly ^{12}C, 3-100 GeV, NOMAD)

The model

- Our aim: realistic description of CCQE in nuclei

  compare to MiniBooNE data (modified Smith-Moniz ansatz)
- Relevant hadronic degrees of freedom: π, N, Δ(1232)

- Ingredients:
  - Elementary process $\nu_\mu \, n \rightarrow \mu^- \, p$
  - Fermi motion
  - Pauli blocking
  - Nuclear binding
  - Nucleon spectral functions
  - Medium polarization (RPA)

and also

  - Non CCQE background (cannot be separated from CCQE in a model independent way)

The model

- Elementary amplitude for $\nu_\mu(k)\, n(p) \to \mu^-(k')\, p(p')$

$$\mathcal{M} = \frac{G_F \cos\theta_C}{\sqrt{2}} l^\alpha J_\alpha$$

where $l^\alpha = \bar{u}(k')\gamma^\alpha(1-\gamma_5)u(k)$ and

$$J_\alpha = \bar{u}(p')\left[\left(\gamma_\alpha - \frac{\not{q}\, q_\alpha}{q^2}\right) F_1^V + \frac{i}{2M}\sigma_{\alpha\beta}q^\beta F_2^V + \gamma_\mu\gamma_5 F_A + \frac{q_\mu}{M}\gamma_5 F_P\right] u(p)$$

$F_{1,2}^V(Q^2)$ ← BBBA07 $\qquad Q^2 = -(k-k')^2$

$$F_A(Q^2) = g_A\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}, \quad F_P(Q^2) = \frac{2M^2}{Q^2+m_\pi^2} F_A(Q^2)$$ ← PCAC

$g_A = 1.26$ ← neutron β decay $\qquad M_A = 1\ \mathrm{GeV}$

Using PCAC and π-pole dominance: $\dfrac{g_A}{2f_\pi} = \dfrac{f_{NN\pi}}{m_\pi}$ ← Goldberger-Treiman

The model

- Local Fermi Gas

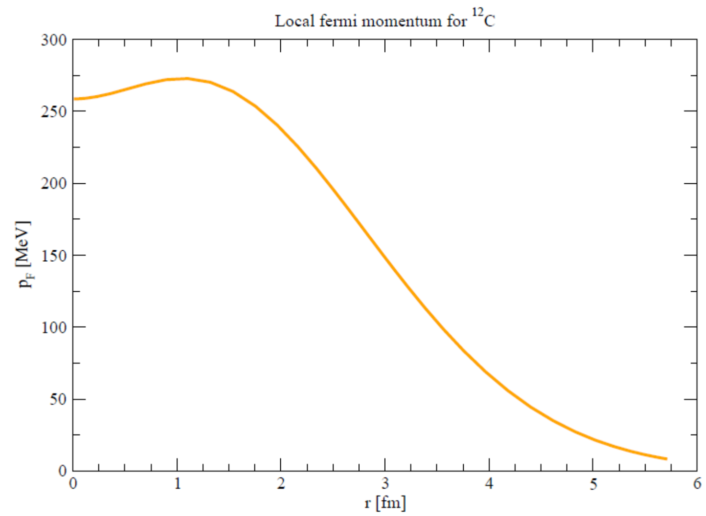
$$p_F(r) = [\tfrac{3}{2}\pi^2\rho(r)]^{1/3}$$

  - Fermi Motion of initial nucleons:

$$f(\vec{r},\vec{p}) = \Theta(p_F(r) - |\vec{p}|)$$

  - Pauli blocking of final nucleons:

$$P_{\text{Pauli}} = 1 - \Theta(p_F(r) - |\vec{p}|)$$



- Mean field potential
  - Density and momentum dependent
  - Parameters fixed in p-Nucleus scattering Teis et. al., Z. Phys. A 346 (1997) 421
  - Nucleons acquire effective masses

$$M_{\text{eff}} = M + U(\vec{r},\vec{p})$$

The model

- Spectral functions
  - The momentum distribution of a nucleon with 4-momentum p is

$$S(p) = -\frac{1}{\pi} \frac{\mathrm{Im}\Sigma(p)}{[p^2 - M^2 - \mathrm{Re}\Sigma(p)]^2 + [\mathrm{Im}\Sigma(p)]^2}$$

Σ ⟵ nucleon selfenergy

  - For final nucleons (above the Fermi sea)

$$\mathrm{Im}\Sigma = -\sqrt{(p^2)}\Gamma_{\mathrm{coll}}(p,r)\,,\ \Gamma_{\mathrm{coll}} = \langle \sigma_{NN} v_{\mathrm{rel}} \rangle$$

⟵ collisional broadening GiBUU

  - $\mathrm{Re}\Sigma$ is obtained from $\mathrm{Im}\Sigma$ with a dispersion relation assuming that at the pole position:

$$p_0^{(pole)} = \sqrt{\vec{p}^2 + M_{\mathrm{eff}}^2}$$

  - For initial nucleons (holes) we take $\mathrm{Im}\Sigma \approx 0$

$$S(p) \to \delta(p^2 - M_{\mathrm{eff}}^2)$$

The model

- RPA nuclear correlations

  "In nuclei, the strength of electroweak couplings may change from their free nucleon values due to the presence of strongly interacting nucleons"

  Singh, Oset, NPA 542 (1992) 587

  - For the axial coupling g_A :

$$\frac{(g_A)_{\text{eff}}}{g_A} = \frac{1}{1 + g' \chi_0}$$

χ_0 dipole susceptibility

g' Lorentz-Lorenz factor ~1/3

Ericson, Weise, Pions in Nuclei

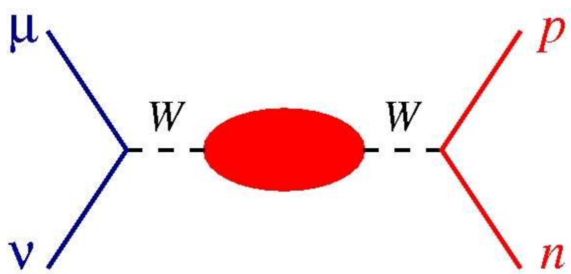
  - The quenching of g_A in Gamow-Teller β decay is well established

$$\frac{(g_A)_{\text{eff}}}{g_A} \sim 0.9$$

Wilkinson, NPA 209 (1973) 470

The model

- RPA nuclear correlations
  - Following Nieves et. al. PRC 70 (2004) 055503 :



$$V_{NN} = \vec{\tau}_1 \vec{\tau}_2 \sigma_1^i \sigma_2^j [\hat{q}_i \hat{q}_j V_L(q) + (\delta_{ij} - \hat{q}_i \hat{q}_j) V_T(q)] + g \vec{\sigma}_1 \vec{\sigma}_2 + f' \vec{\tau}_1 \vec{\tau}_2 + f I_1 I_2$$

  - In particular

$$V_L = \frac{f_{N N \pi}^2}{m_\pi^2} \left\{ \left(\frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - q^2} \right)^2 \frac{\vec{q}^{\,2}}{q^2 - m_\pi^2} + g' \right\} \quad g' = 0.6 \ (\pm 0.1)$$

  - π spectral function changes in the nuclear medium ➡ so does J_α^A

The model

- RPA nuclear correlations

  - RPA approach built up with single-particle states in a Fermi sea
  - Simplified vs. some theoretical models (e.g. continuum RPA)
  - Applies to inclusive processes; not suitable for transitions to discrete states

  But

  - Incorporates explicitly π and ρ exchange and Δ-hole states
  - Can be inserted in a unified framework to study QE, 1π, N-knockout, etc
  - 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 at MiniBooNE energies

The model

- Non CCQE background (GiBUU transport model)
  - Most relevant processes:

$$\nu_\mu N \rightarrow \mu^- \Delta$$

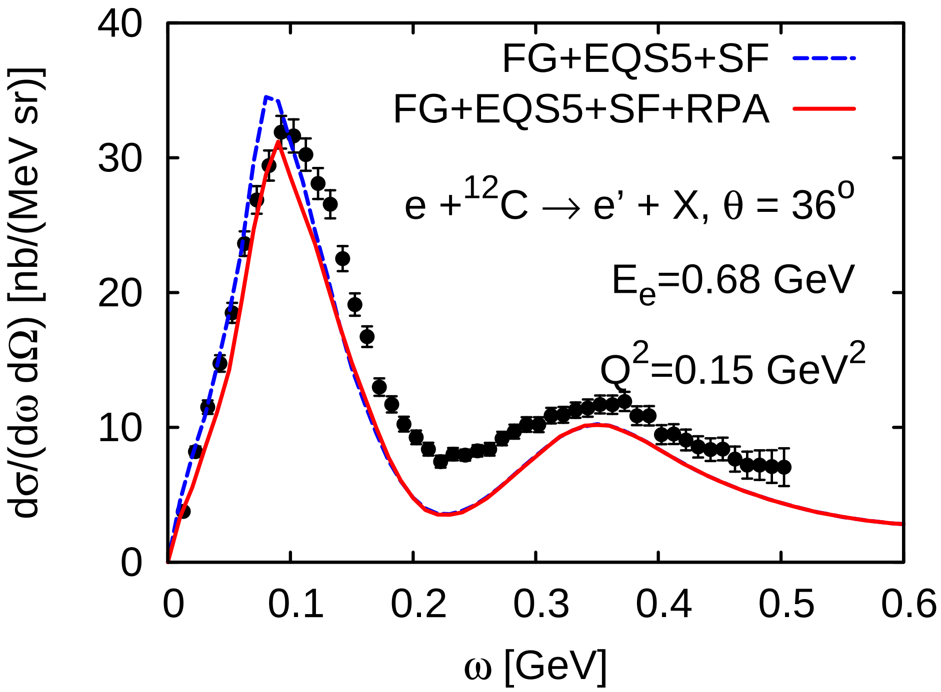
followed by $\Delta N \rightarrow N N$ (π less decay mode)

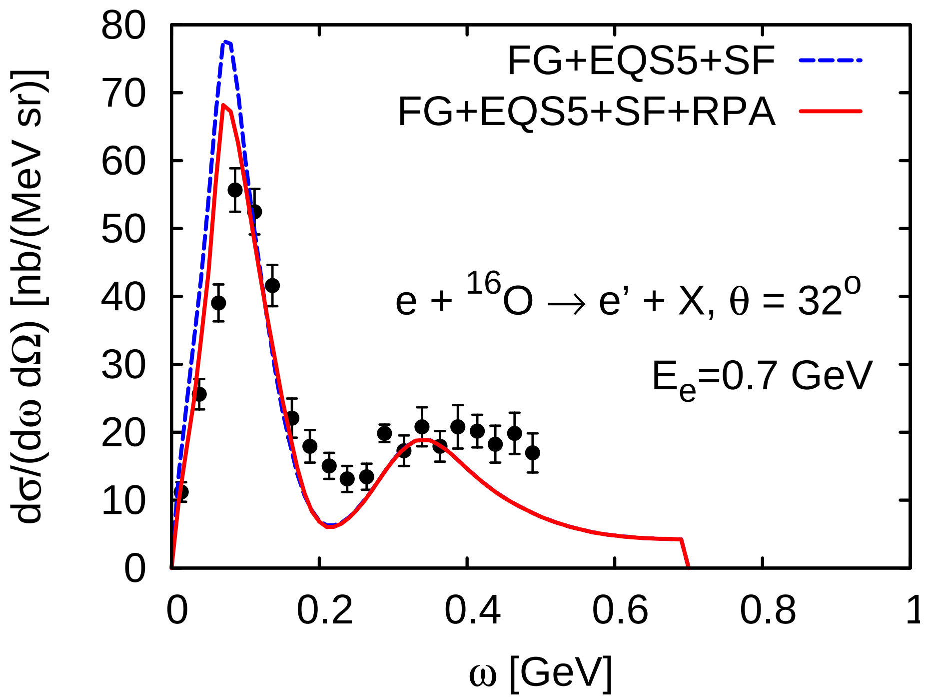
or by $\Delta \rightarrow N \pi$ and then $\pi N N \rightarrow N N$ (π absorption)

  - Details in the talk by Tina Leitner

Results

- Comparison to inclusive electron scattering data

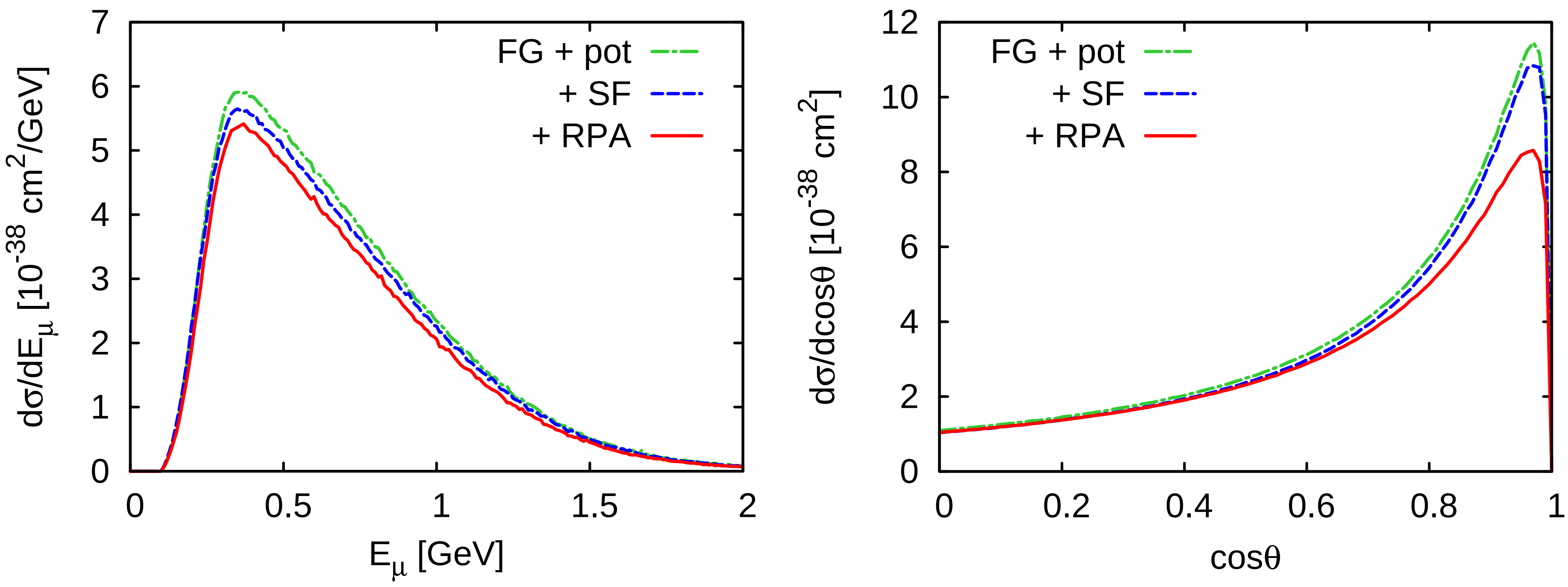




- Missing strength in the deep region:
  more complete many-body dynamics required Gil et. al., NPA 627 (1997) 543
- RPA less relevant than in the weak case

Results

- Differential cross sections averaged over the MiniBooNE flux



Results

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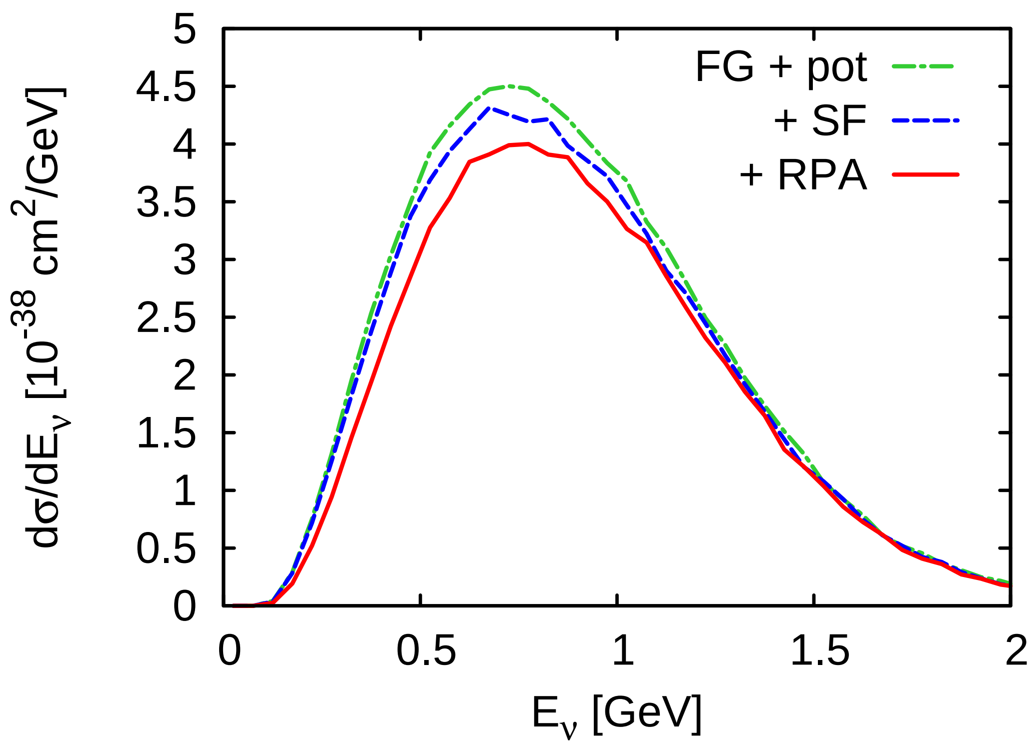
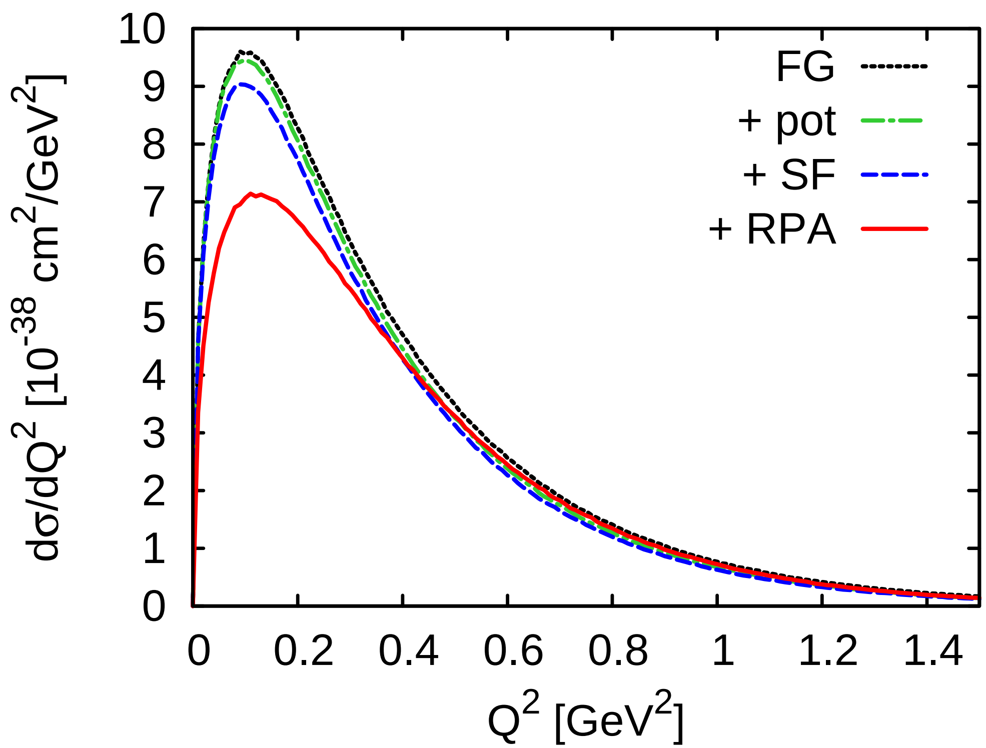
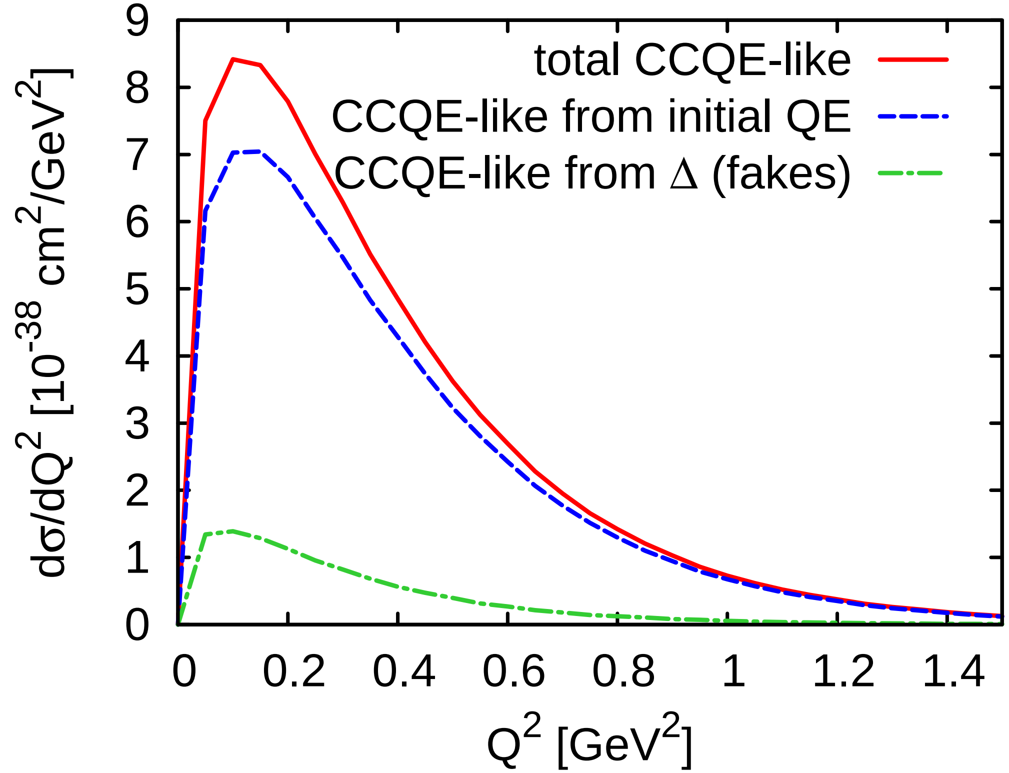




- RPA correlations cause a considerable reduction of the c.s. at low Q^2 and forward angles

Results

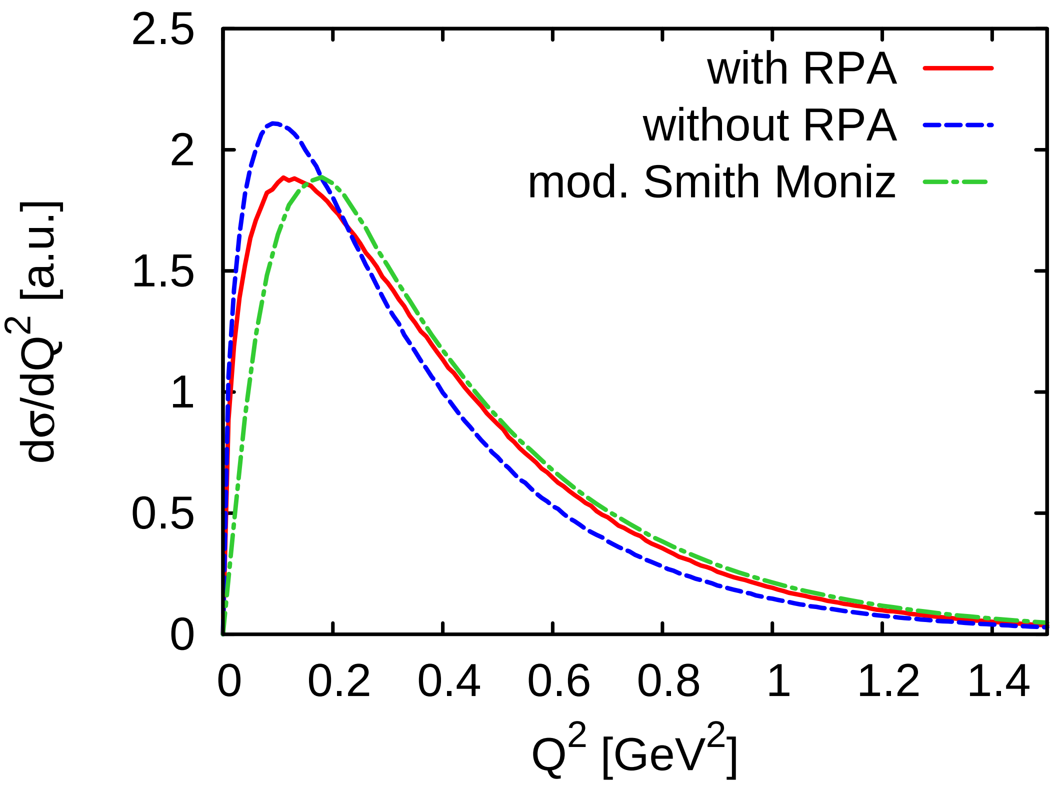
- CCQE + non-CCQE background (measured quantity)



$$\frac{\text{non}-\text{CCQE}}{\text{total CCQE}-\text{like}} = 0.1$$

Results

- Comparison to the modified Smith-Moniz ansatz (shape)

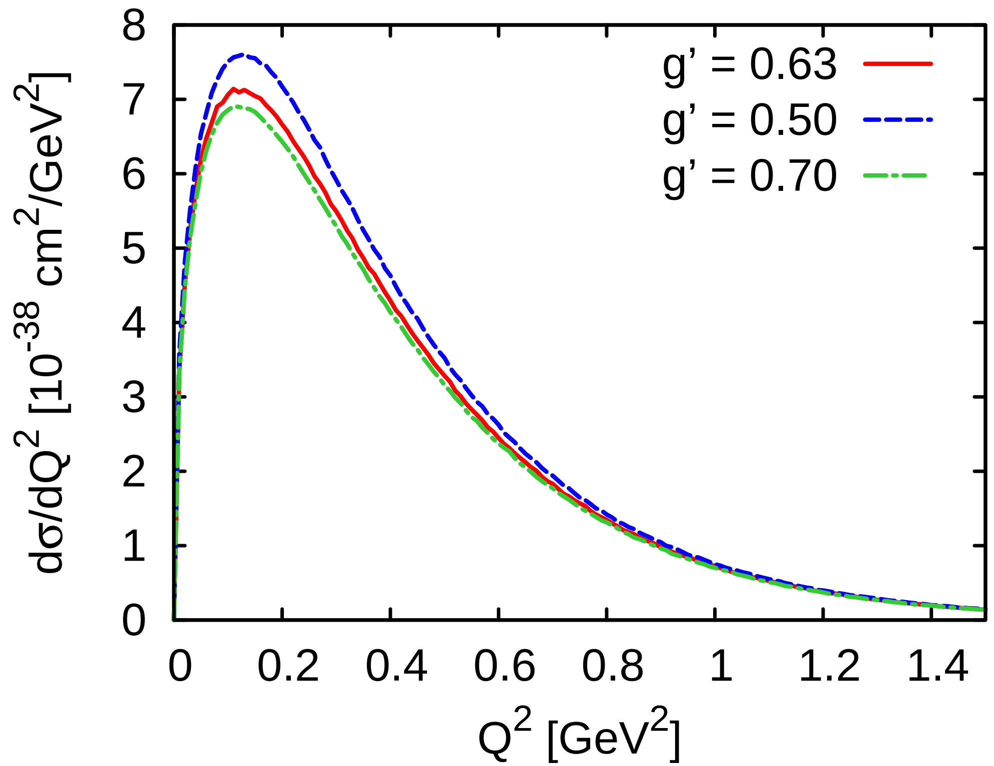


All curves are normalized to the same area

- The effect of RPA brings the shape of the Q^2 distribution closer to experiment keeping M_A = 1 GeV

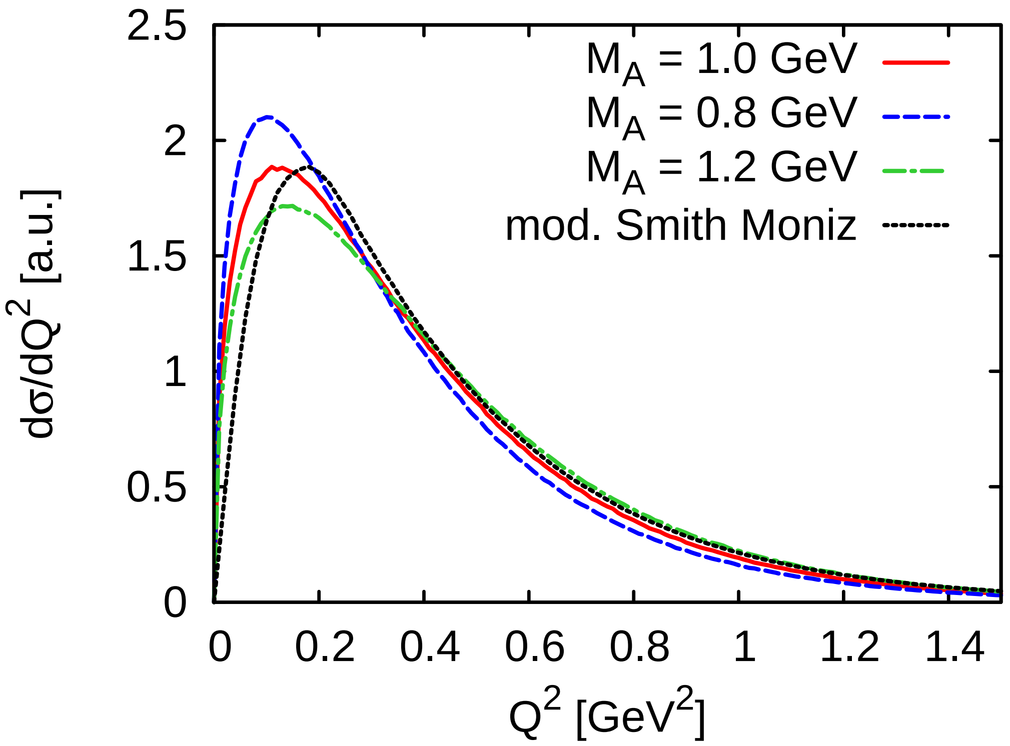
Results

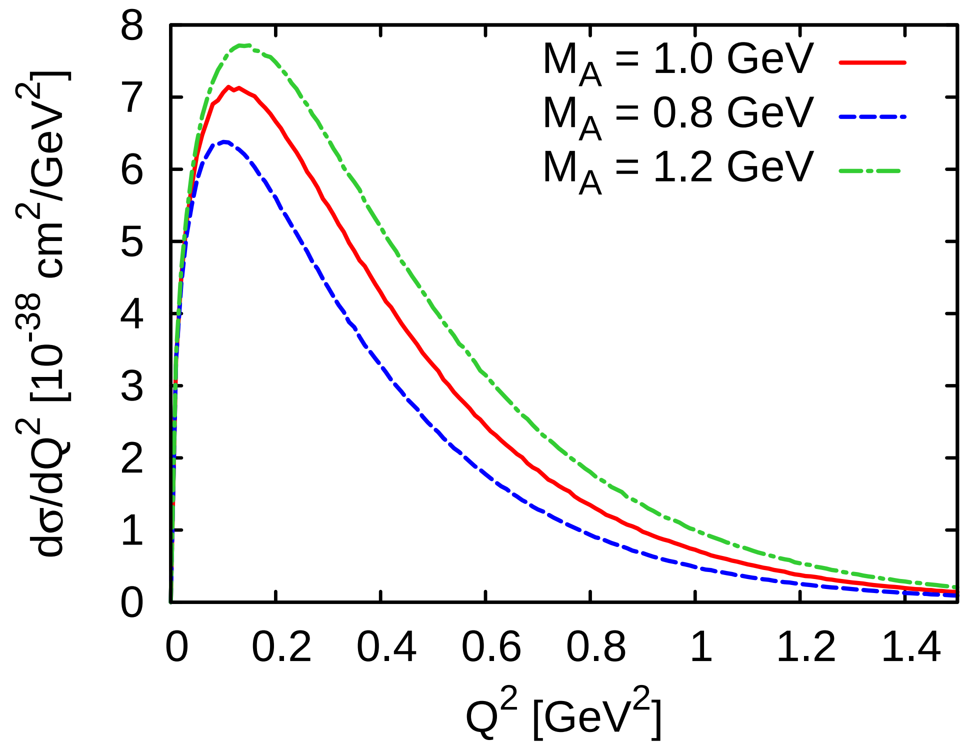
- Changing g' = 0.5-0.7
  - Leaves the shape unaltered
  - Small changes in the integrated cross section $\langle\sigma\rangle$ =3.1-3.4 $\times$ 10^{-38} cm^2



Results

- Changing M_A





- The experimental shape is better described with M_A=1 GeV

- There are large differences in the integrated cross section

M_A [GeV]	0.8	1.0	1.2
$\langle\sigma\rangle$ [$\times$ 10^{-38}cm^2]	2.5	3.2	3.7

Conclusions

- We have developed a model for CCQE starting form a Local Fermi Gas but incorporating important many body corrections: nucleon spectral functions, medium polarization (RPA).
- RPA: strong reduction at low q^2 (quenching)
- Good description of the shape of the MiniBooNE q^2 distribution with M_A=1 GeV
- A larger integrated CCQE cross section would require M_A>1 GeV

Conclusions

- There is (nuclear) physics beyond the naive Fermi Gas Model.

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