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Theoretical highlights on neutrino-nucleus interactions: current challenges

Luis Alvarez-Ruso

Universidade de Coimbra

Introduction

- Neutrino-nucleus interactions are important for:
  - Oscillation experiments
    - ν detection, E_ν reconstruction, ν flux calibration
    - Electron-like backgrounds:
      - NC π^o production (incoherent, coherent)
      - Photon emission in NC
  - Hadronic physics
    - Nucleon and Nucleon-Resonance (N-Δ, N-N*) axial form factors
    - Strangeness content of the nucleon spin
  - Nuclear physics
    - Information about: nuclear correlations, MEC, spectral functions
    - nuclear effects: essential for the interpretation of the data

Introduction

- Most relevant processes in the few-GeV region:
  - Quasielastic scattering
  - Single pion production (incoherent and coherent)

QE scattering

- ν detection: $\nu_\mu \, n \to \mu^- \, p$
- E_ν reconstruction:
  - Assumes that $E_\nu = \dfrac{2 m_n E_\mu - m_\mu^2 - m_n^2 + m_p^2}{2(m_n - E_\mu + p_\mu \cos\theta_\mu)}$
  - Important for oscillations: $P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{23} \, \sin^2 \dfrac{\Delta m_{23}^2 L}{2 E_\nu}$
- QE σ affect the expected sensitivities to oscillation parameters
  - Example: Fernandez, Meloni, arXiv:1010.2329
  - β beam hypothetical exp.: $< E_\nu > 0.3$ GeV, ^{16}O target
  - Sensitivities to θ_{13} and δ_{CP} vary ~ 10-30 % depending on the nuclear CCQE model

ν QE scattering

- The (CC) elementary process: $\nu_\mu(k)\, n(p) \rightarrow \mu^-(k')\, p(p')$

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

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

$$J_\alpha = \bar{u}(p')\left[\gamma_\alpha F_1^V + \frac{i}{2M}\sigma_{\alpha\beta}q^\beta F_2^V + \gamma_\mu\gamma_5 F_A + \frac{q_\mu}{M}\gamma_5 F_P\right]u(p)$$

- Vector form factors: $F_{12}^V = F_{12}^p - F_{12}^n$ extracted from e-p, e-d data
- Axial form factors:

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

dipole ansatz

PCAC

ν QE scattering

- The (CC) elementary process: $\nu_\mu(k)\, n(p) \to \mu^-(k')\, p(p')$

$$F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

  - g_A = 1.267 $\leftarrow$ β decay
  - M_A= 1.016 $\pm$ 0.026 GeV ($\nu d\,, \bar{\nu} p$) Bodek et al., EPJC 53 (2008)
  - M_A from π electroproduction on p:
    - Connected to F_A at threshold and in the chiral limit (m_π =0)
    - Using models to connect with data $\Rightarrow$
    - M_A^{ep}= 1.069 $\pm$ 0.016 GeV Liesenfeld et al., PLB 468 (1999) 20
    - A more careful evaluation in ChPT Bernard et al., PRL 69 (1992) 1877

$$\langle r_A^2 \rangle_e = \langle r_A^2 \rangle_\nu + \frac{3}{64 f_\pi}\left(1 - \frac{12}{\pi^2}\right) \,, \langle r_A^2 \rangle = \frac{12}{{M_A}^2}$$

    - $M_A = M_A^{ep}$ - ΔM_A , ΔM_A =0.055 GeV $\Rightarrow$ M_A = 1.014 GeV

ν QE scattering

- Relativistic Global Fermi Gas Smith, Moniz, NPB 43 (1972) 605
  - Impulse Approximation
  - Fermi motion $f(\vec{r},\vec{p}) = \Theta(p_F - |\vec{p}|)$
  - Pauli blocking $P_{\text{Pauli}} = 1 - \Theta(p_F - |\vec{p}|)$
  - Average binding energy $E = \sqrt{\vec{p}^2 + m_N^2} - \epsilon_B$
  - Explains the main features of the (e,e') inclusive σ in the QE region
  - Fails in the details (nuclear dynamics needed)

ν QE scattering

- Spectral functions of nucleons in nuclei

Benhar et al., PRD 72 (2005)
Ankowski, Sobczyk, PRC 67 (2008)
Nieves et al., PRC 70 (2004)
Leitner et al., PRC 79 (2009)

  - The nucleon propagator can be cast as

$$G(p) = \int d\omega \frac{S_h(\omega, \vec{p})}{p^0 - \omega - i\epsilon} + \int d\omega \frac{S_p(\omega, \vec{p})}{p^0 - \omega + i\epsilon}$$

  - $S_{h(p)} \leftarrow$ hole (particle) spectral functions: 4-momentum (p) distributions of the struck (outgoing) nucleons

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

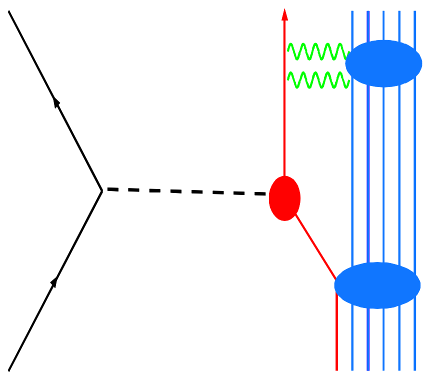
  - $\Sigma \leftarrow$ nucleon selfenergy
  - Better description of (e,e') inclusive σ

ν QE scattering

- Relativistic mean field
  - Impulse Approximation
  - Initial nucleon in a bound state (shell)
    - Ψ_i : Dirac eq. in a mean field potential (ω-σ model)
  - Final nucleon
    - PWIA
    - RDWIA: Ψ_f : Dirac eq. for scattering state
    - Glauber

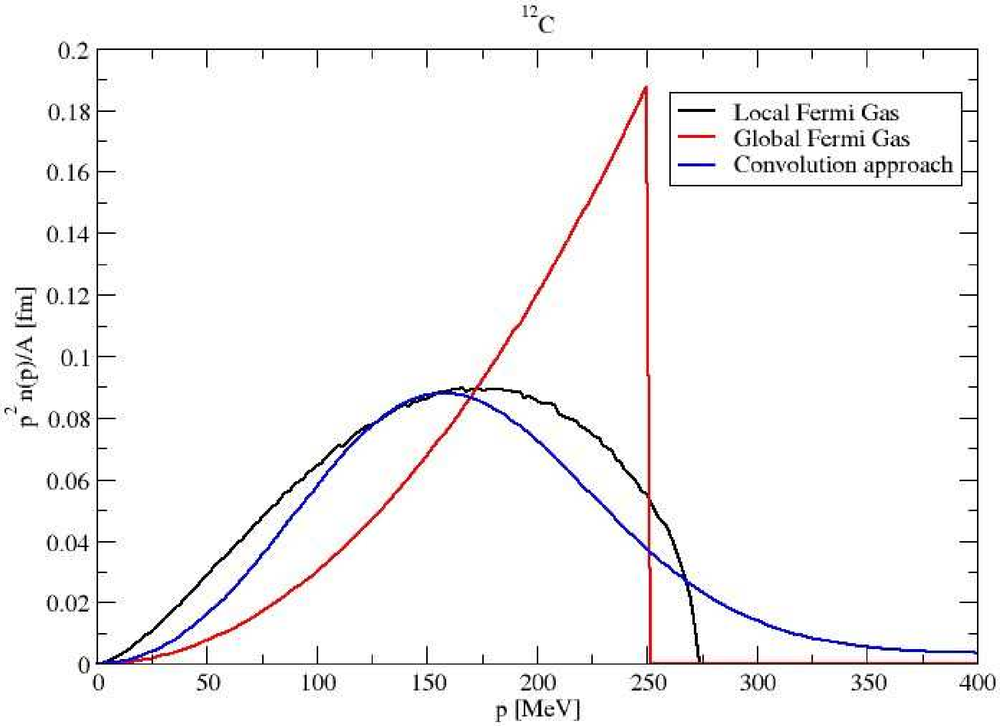
  } Complex optical potential
  - Problem: nucleon absorption that reduces the c.s.
  - Can be used to study:
    - 1N knockout
    - inclusive processes: with only Re[V_{opt}]

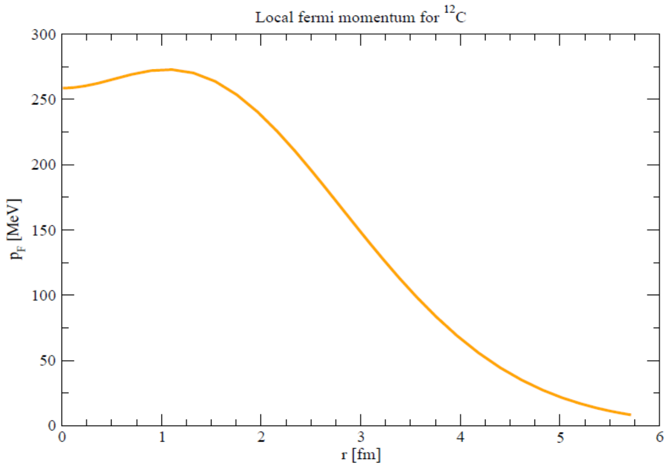
Martinez et al., PRC 73 (2006)
Budkevich, Kulagin, PRC 76 (2007)



ν QE scattering

- Local Fermi Gas $p_F(r) = [\frac{3}{2}\pi^2\rho(r)]^{1/3}$





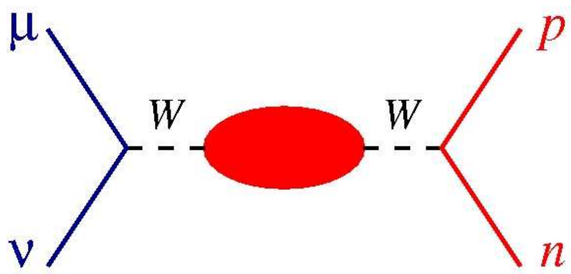
Convolution model:
Ciofi degli Atti, Simula, PRC 53 (1996)

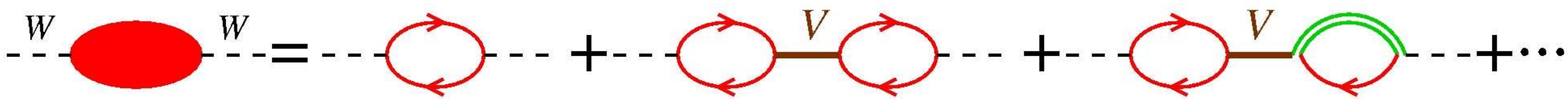
- Space-momentum correlations absent in the GFG
- Reasonable for medium/heavy nuclei
- Microscopic many-body effects are tractable (calculations in infinite nuclear matter)

ν QE scattering

- RPA long range correlations

Singh, Oset, NPA 542 (1992)
Marteau, Delorme, Ericson, NIMA 76 (2000)
Nieves et al., PRC 70 (2004)

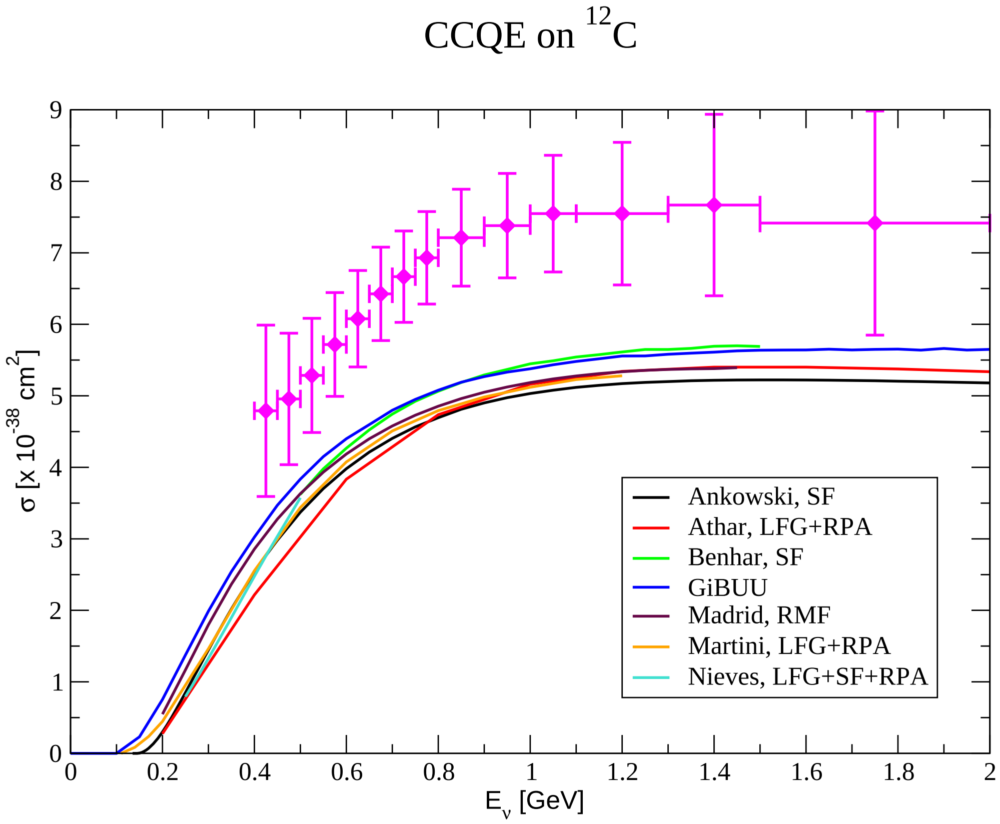




- Incorporates N-hole and Δ-hole states
- V: π, ρ exchange, Landau-Migdal parameter g'
- Describes correctly μ capture on ^{12}C and LSND CCQE
- Collective effect: important at low Q^2 for ν QE

ν QE scattering

- Comparison to MiniBooNE σ

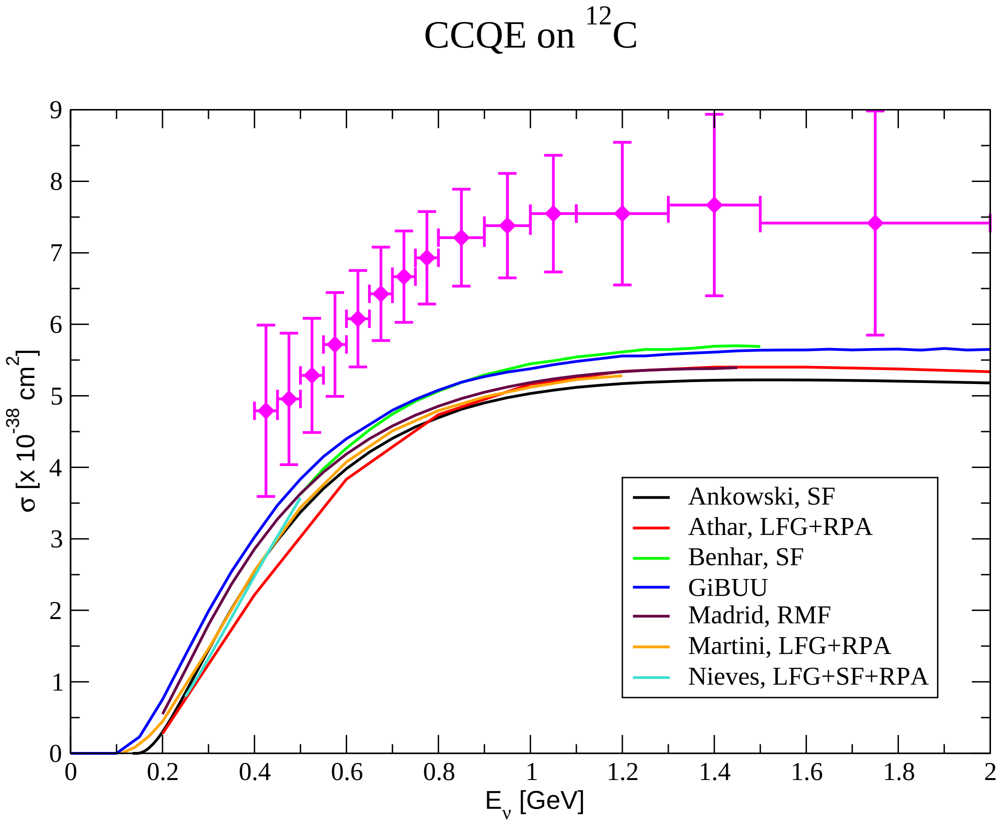


Source: Boyd et al., AIP Conf. Proc. 1189
Data: MiniBooNE, PRD 81, 092005 (2009)

- At $E\nu$ =0.8 GeV: σ_{th} ~ 4.5-5 < σ_{MB} ~ 7 $\times$ 10^{-38} cm^2
- CCQE models with M_A~1 GeV cannot reproduce MiniBooNE σ

ν QE scattering

- Comparison to MiniBooNE σ

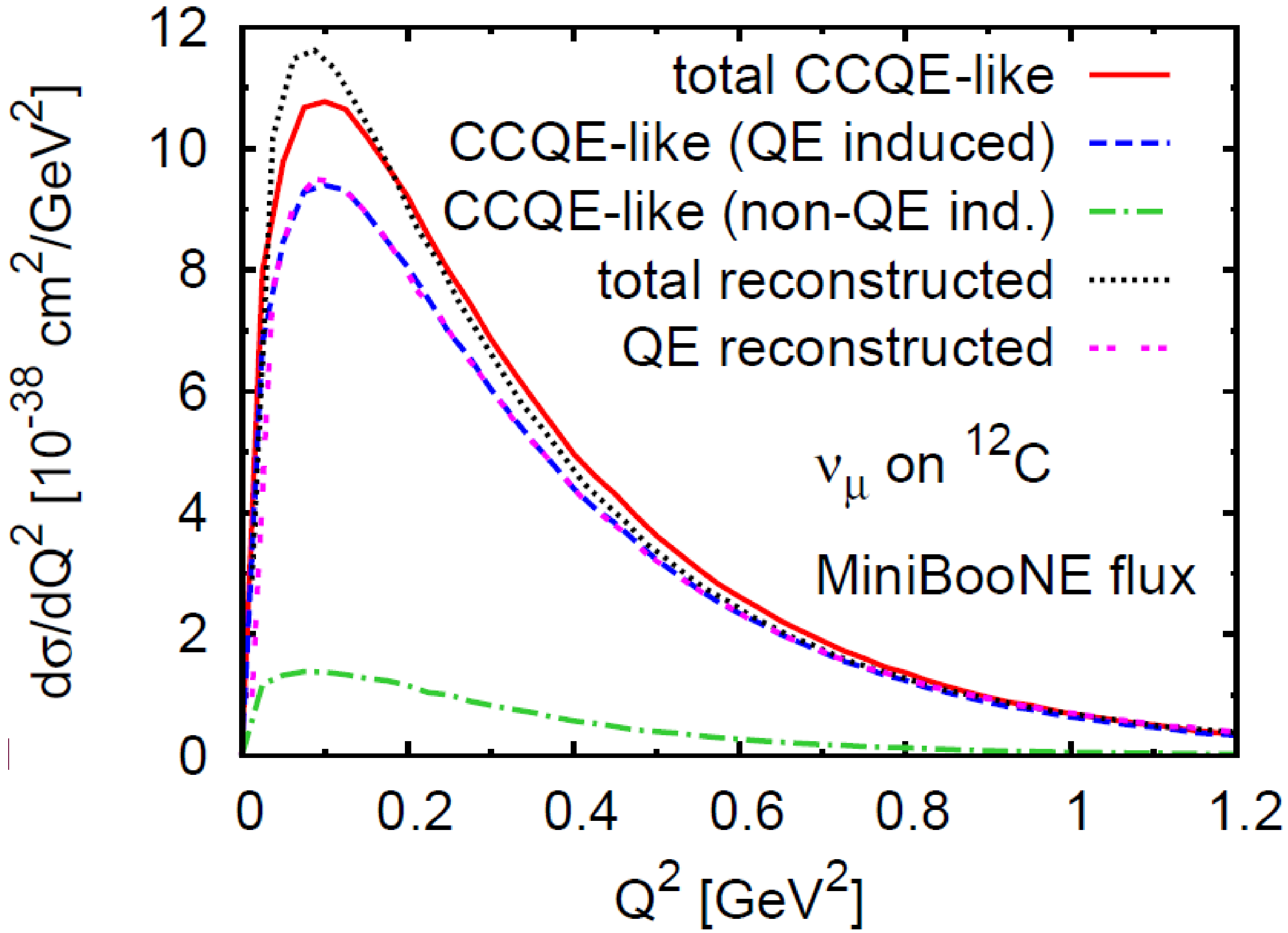


Source: Boyd et al., AIP Conf. Proc. 1189
Data: MiniBooNE, PRD 81, 092005 (2009)

- Background (CCQE-like) depends on the π propagation (absorption and charge exchange) model (NUANCE)
- E_ν reconstruction (unfolding)

ν QE scattering

- Comparison to MiniBooNE σ



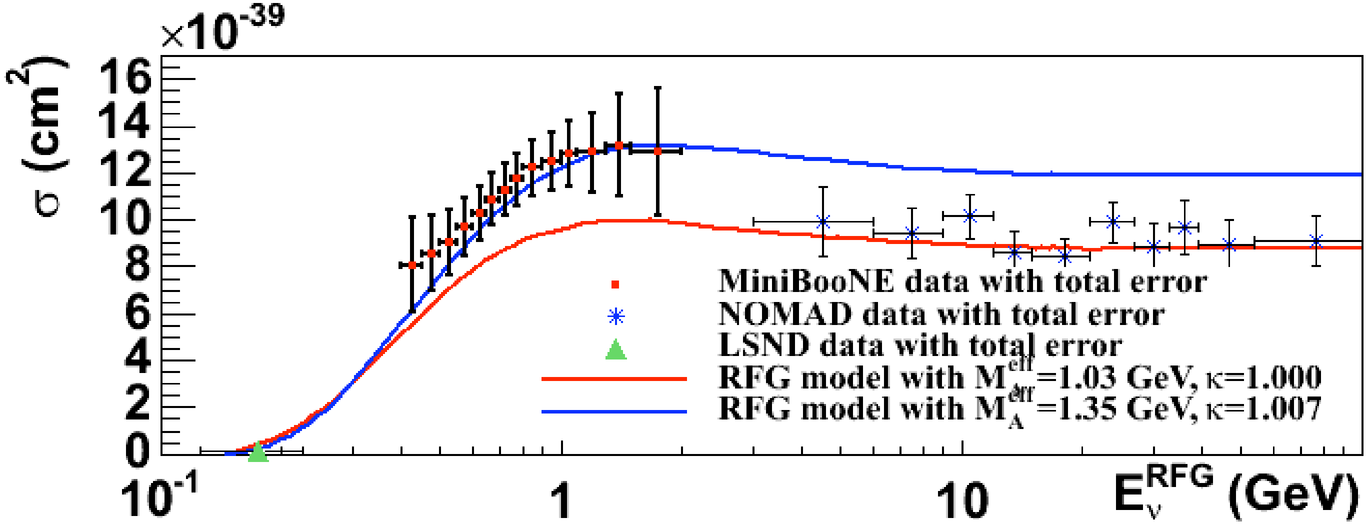
Leitner, Mosel, PRC 81

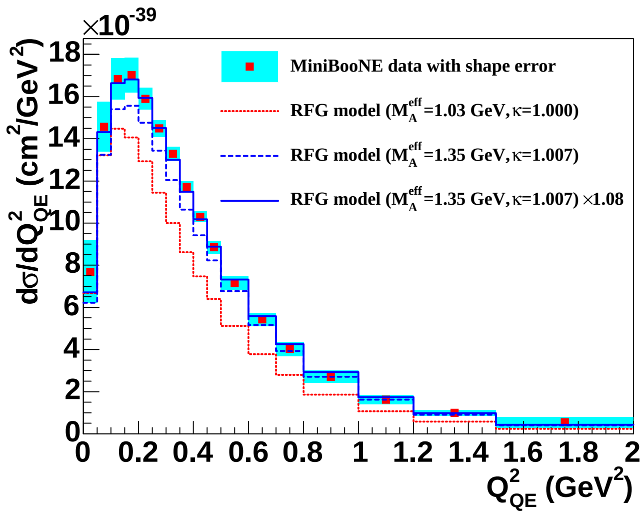
n (absorption and

- E_ν reconstruction (unfolding): good if the CCQE-like background is properly subtracted

ν QE scattering

- Comparison to MiniBooNE σ
  - Proposed solutions:
    - $M_A = 1.35 \pm 0.17$ GeV (RFG)   MiniBooNE, PRD 81, 092005 (2010)

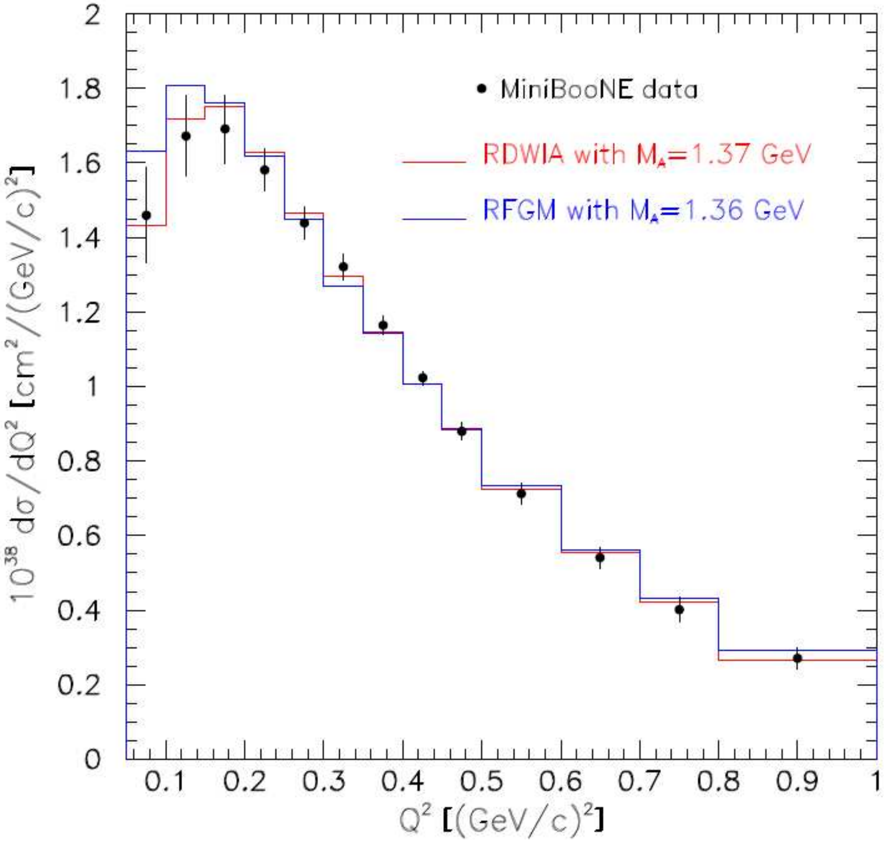




- However, $M_A>1$ GeV is incompatible with:
  - $\nu d\,,\bar{\nu}p$ data
  - π electroproduction on p (at low Q^2)
  - NOMAD: $M_A = 1.05 \pm 0.02(\mathrm{stat}) \pm 0.06(\mathrm{sys})$ GeV Lyubushkin et al., EPJ C63

ν QE scattering

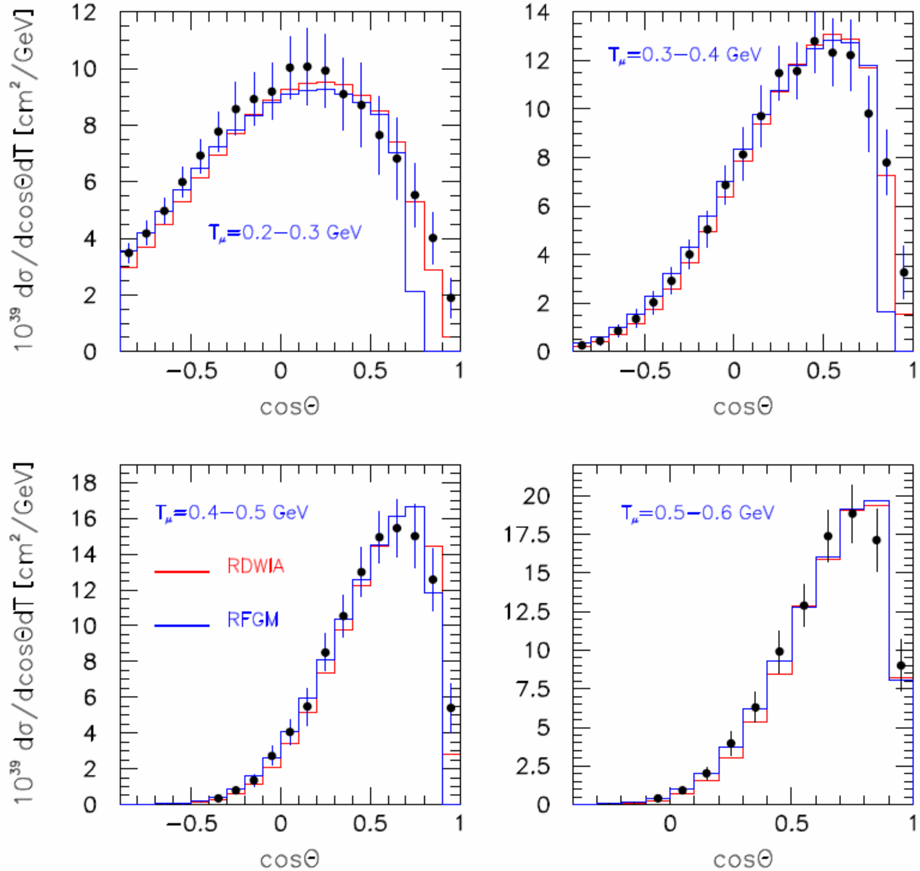
- Comparison to MiniBooNE σ
  - Proposed solutions:
    - M_A=1.37 GeV (RDWIA) Butkevich, arXiv:1006.1595
    - Fit to $d\sigma/dQ^2$ (shape only)



    - Better than RFG at low Q^2

ν QE scattering

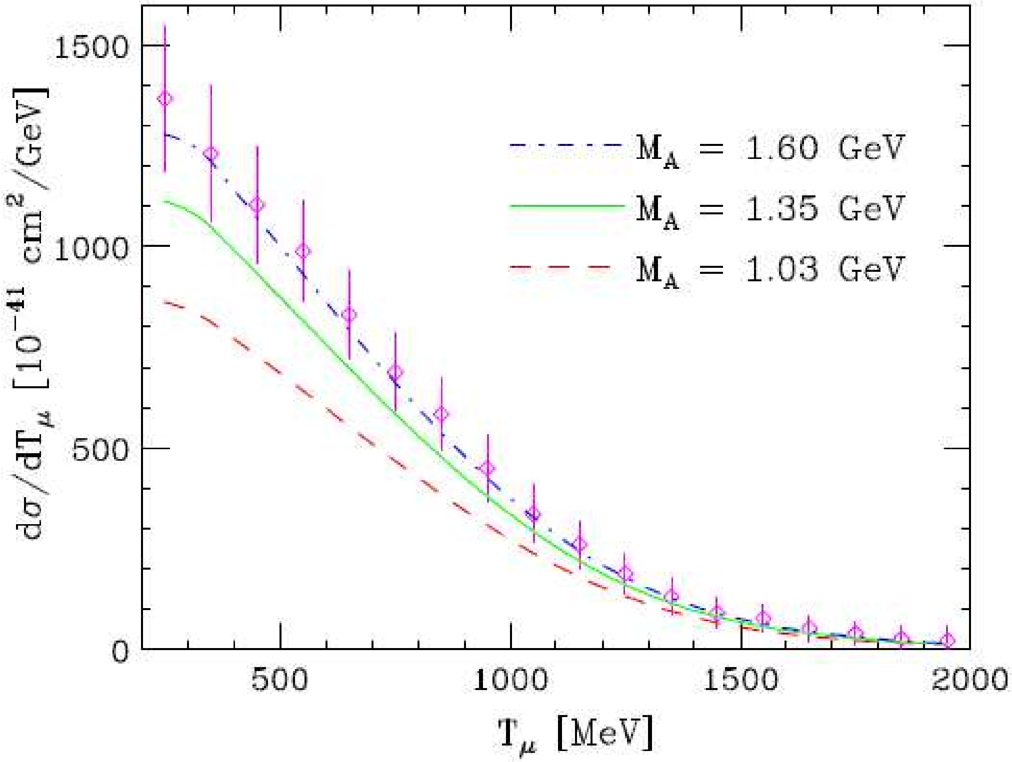
- Comparison to MiniBooNE σ
  - Proposed solutions:
    - M_A=1.37 GeV (RDWIA) Butkevich, arXiv:1006.1595
    - Fit to $d\sigma/dQ^2$ (shape only)

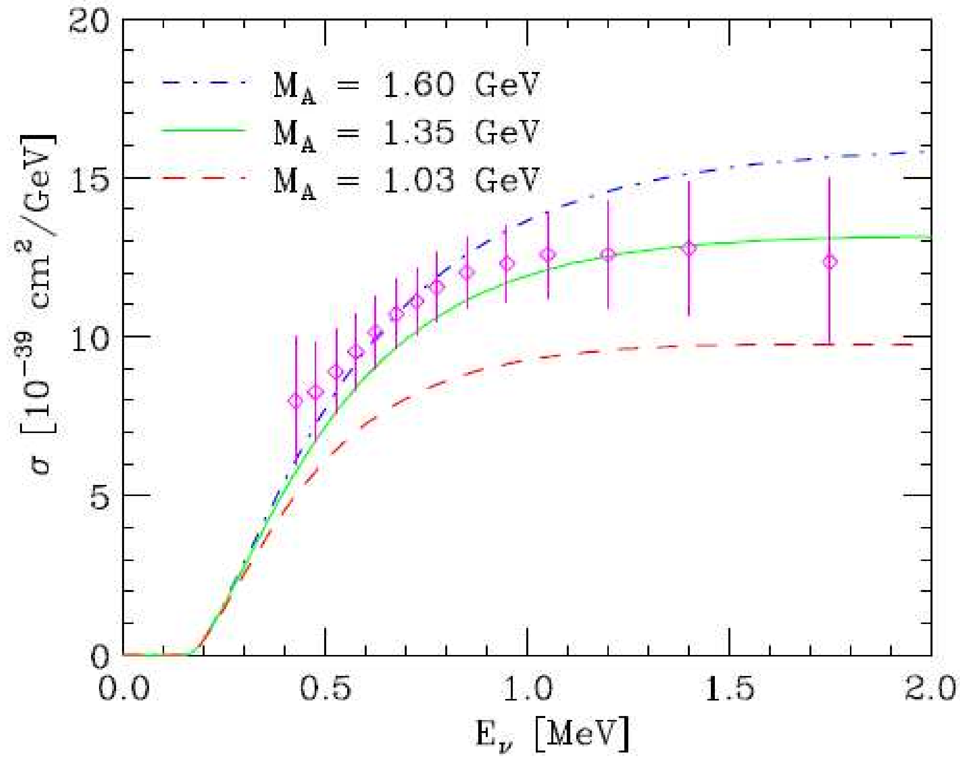


    - Good description of double differential cross section

ν QE scattering

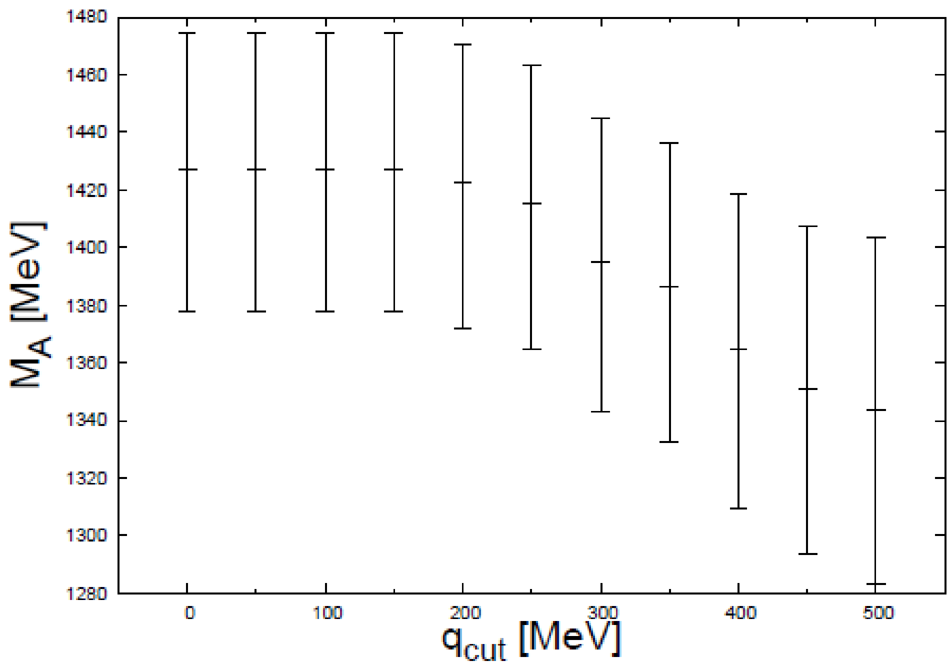
- Comparison to MiniBooNE σ
  - Proposed solutions:
    - M_A=1.6 GeV (Spectral Function) Benhar, Coletti, Meloni, PRL 105 (2010)
    - Fit to $d\sigma/dQ^2$





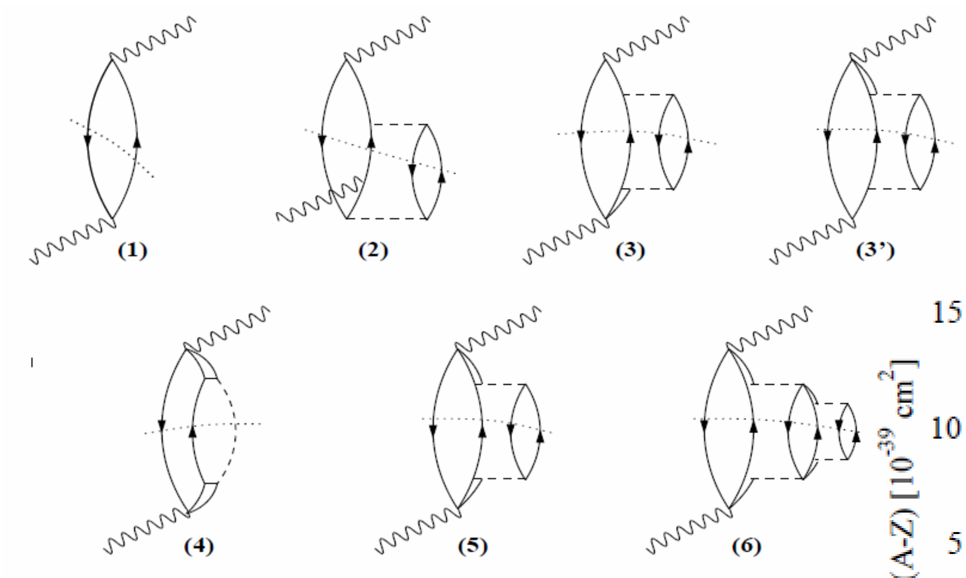
ν QE scattering

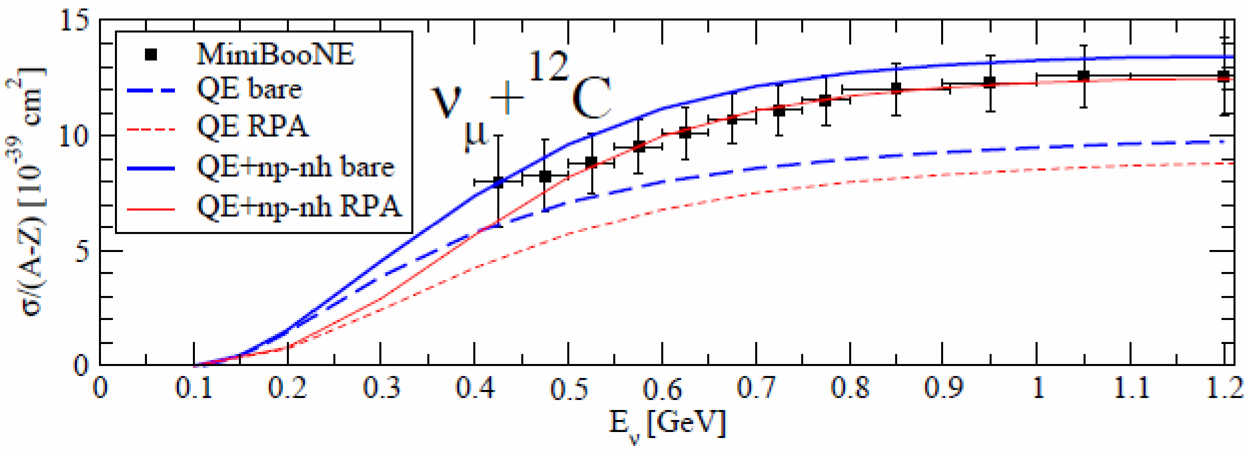
- Comparison to MiniBooNE σ
  - Proposed solutions:
    - M_A=1.343 $\pm$ 0.060 GeV (Spectral Function) Juszczak, Sobczyk, Zmuda, arXiv:1007.2195
    - Fit to double differential c. s. including flux uncertainty
    - Momentum transfer cut q_{cut} = 500 MeV to exclude IA breakdown region: insufficient to reconcile MiniBooNE with exp. on deuterium

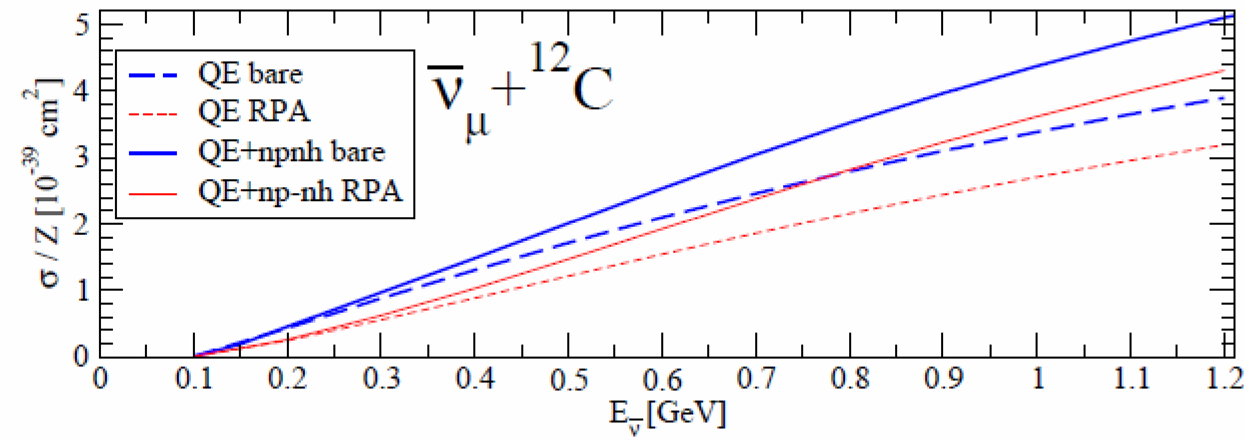


ν QE scattering

- Comparison to MiniBooNE σ
  - Many body RPA Martini et al., PRC 80 (2009), 81 (2010)



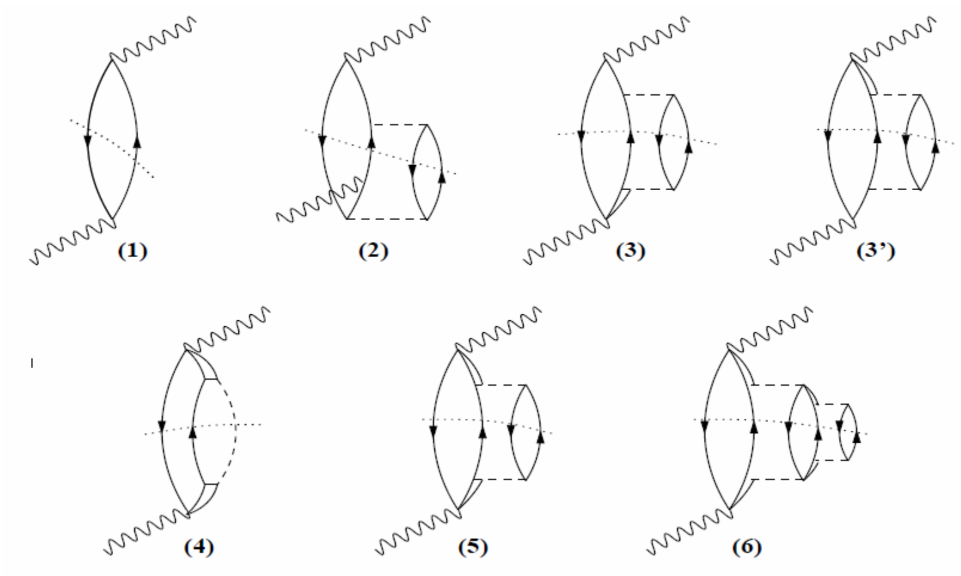


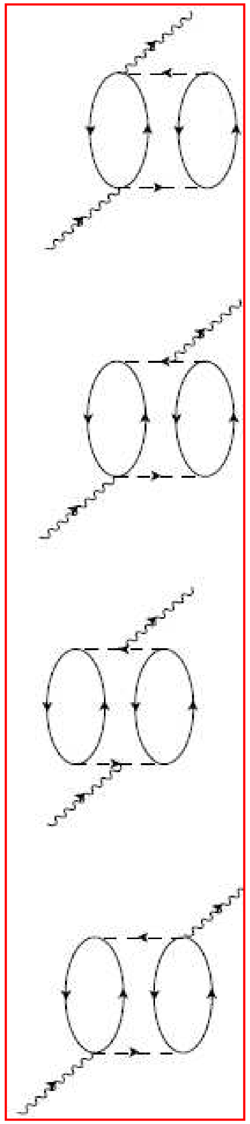


- RPA: small reduction
- Large 2p-2h contribution to ν ^{12}C mainly from (2),(3),(3')

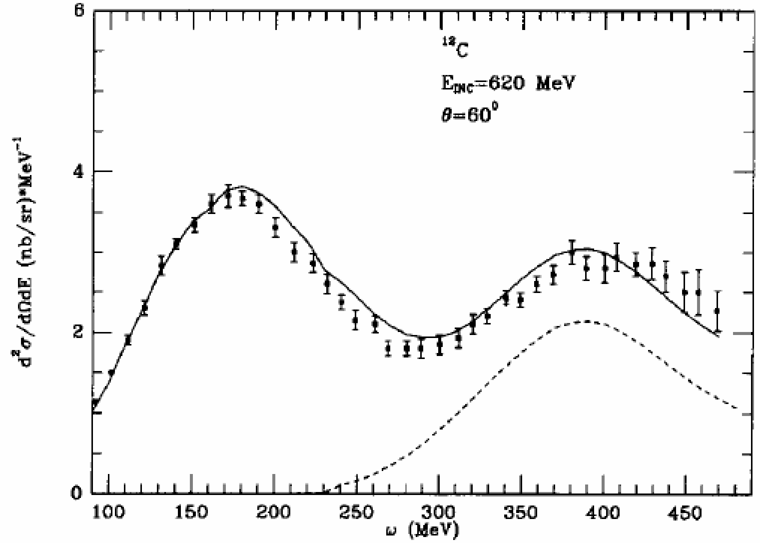
ν QE scattering

- Comparison to MiniBooNE σ
  - Many body RPA Martini et al., PRC 80 (2009), 81 (2010)





$^{12}C(e,e')X$

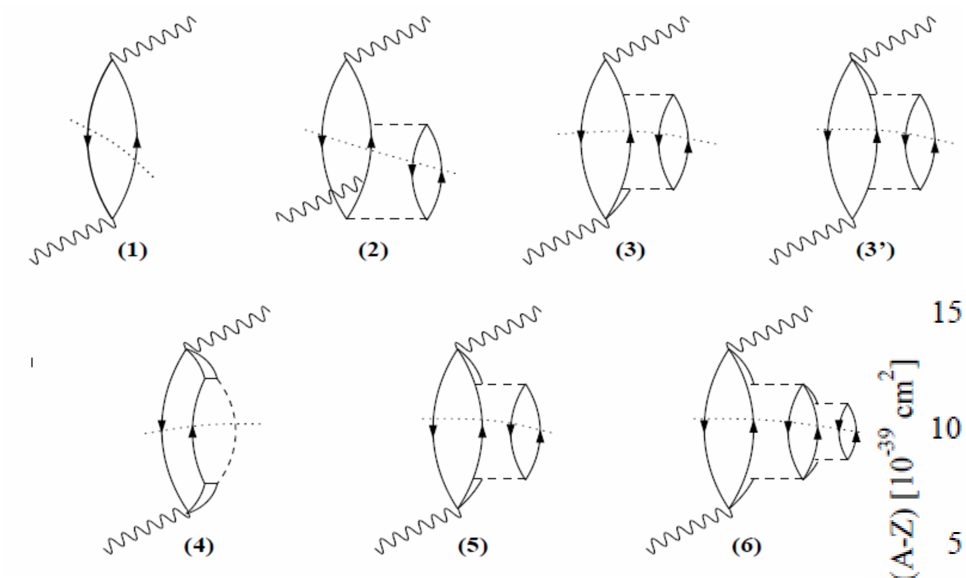


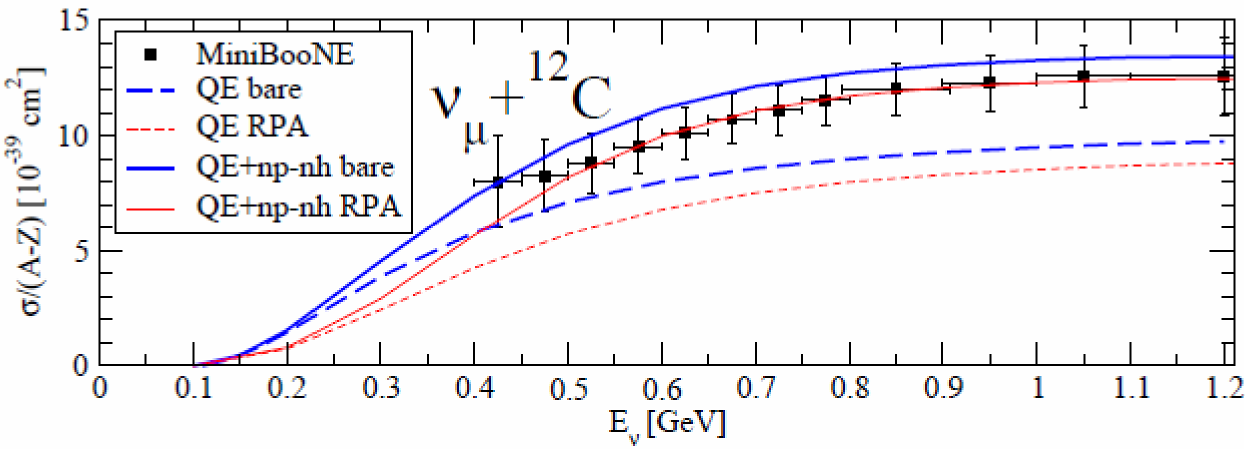
Gil, Nieves, Oset, NPA627

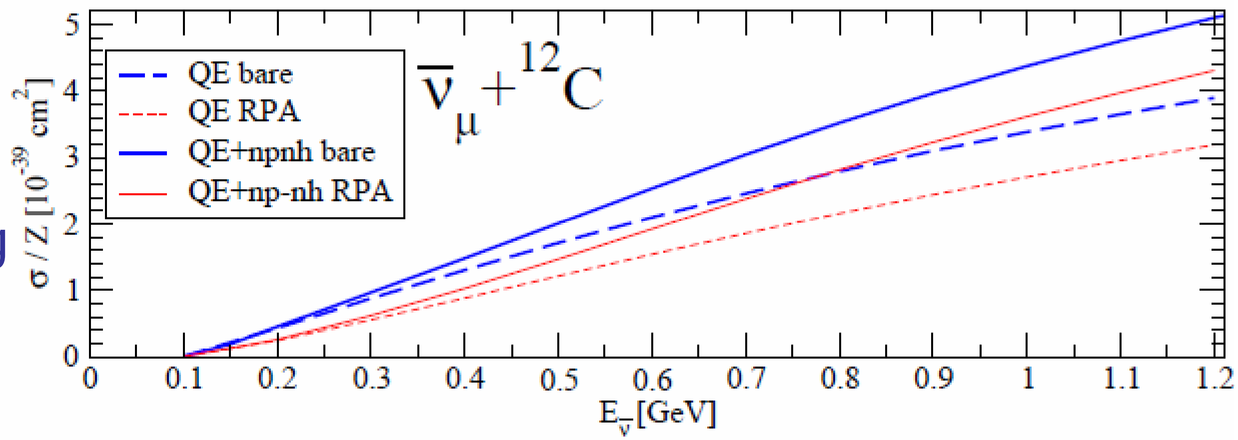
- RPA: small reduction
- Large 2p-2h contribution to ν ^{12}C mainly from (2),(3),(3')
- MEC absent (but important for (e,e') in the dip region)

ν QE scattering

- Comparison to MiniBooNE σ
  - Many body RPA Martini et al., PRC 80 (2009), 81 (2010)





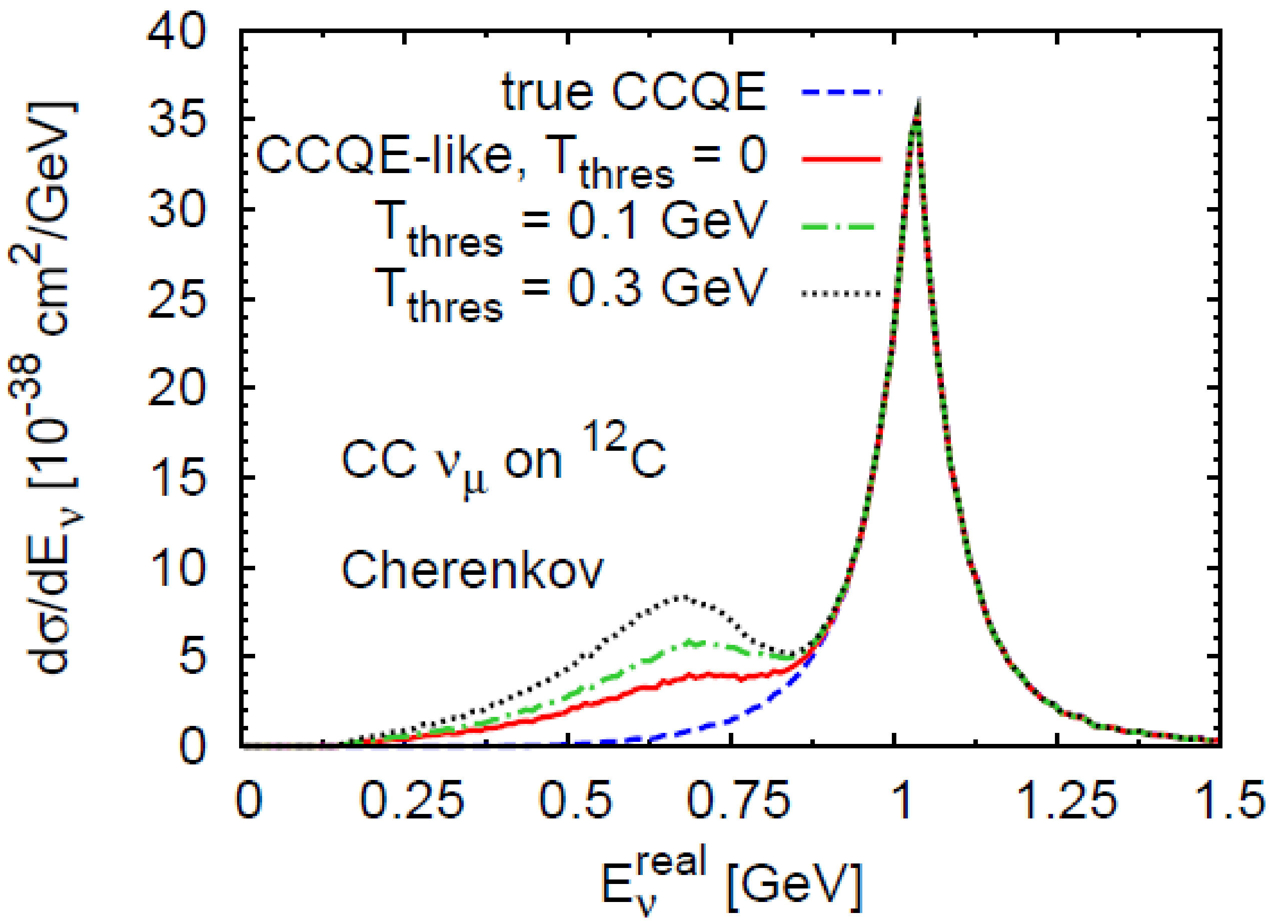


- RPA: small reduction
- Large 2p-2h contribution to ν ^{12}C mainly from (2),(3),(3')
- Prediction: smaller 2p-2h contribution to anti-ν ^{12}C
- Detailed tests against e-scattering data are necessary

1π production

- Reactions
  - Incoherent: $\nu_l \, A \to l \, \pi \, X$
  - Coherent:
    - CC $\nu_l \, A \to l^- \, \pi^+ \, A$
    - NC $\nu \, A \to \nu \, \pi^0 \, A$
- Relevant for oscillations
  - NC π^o: e-like background to $\nu_\mu \to \nu_e$ searches (θ_{13} & $\delta \leftrightarrow$ CP violation)
  - Source of CCQE-like events (in nuclei), needs to be subtracted for a good E_ν reconstruction

1π production



Leitner, Mosel, PRC 81

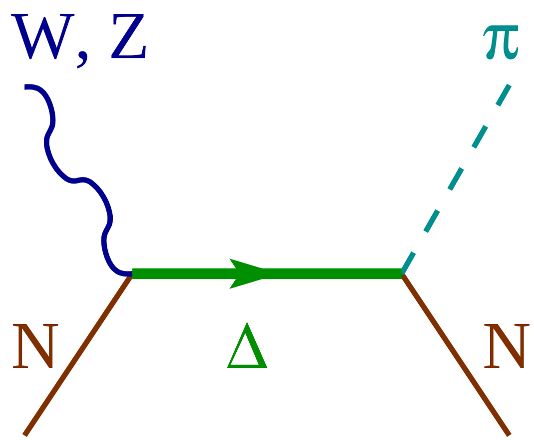
(θ_{13} & $\delta \leftrightarrow$ CP violation)

- Source of CCQE-like events (in nuclei), needs to be subtracted for a good E_ν reconstruction

1π production

- Elementary process: $\nu_l \, N \to l \, \pi \, N'$
  - Dominated by resonance production
  - At Eν ~ 1 GeV: Δ(1232)

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



  - N-Δ transition current:

$$J^\mu = \bar{\psi}_\mu \left[\left(\frac{C_3^V}{M}(g^{\beta\mu} \not{q} - q^\beta \gamma^\mu) + \frac{C_4^V}{M^2}(g^{\beta\mu} q \cdot p' - q^\beta p'^\mu) + \frac{C_5^V}{M^2}(g^{\beta\mu} q \cdot p - q^\beta p^\mu) \right) \gamma_5 \right.$$
$$\left. + \frac{C_3^A}{M}(g^{\beta\mu} \not{q} - q^\beta \gamma^\mu) + \frac{C_4^A}{M^2}(g^{\beta\mu} q \cdot p' - q^\beta p'^\mu) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2} q^\beta q^\mu \right] u$$

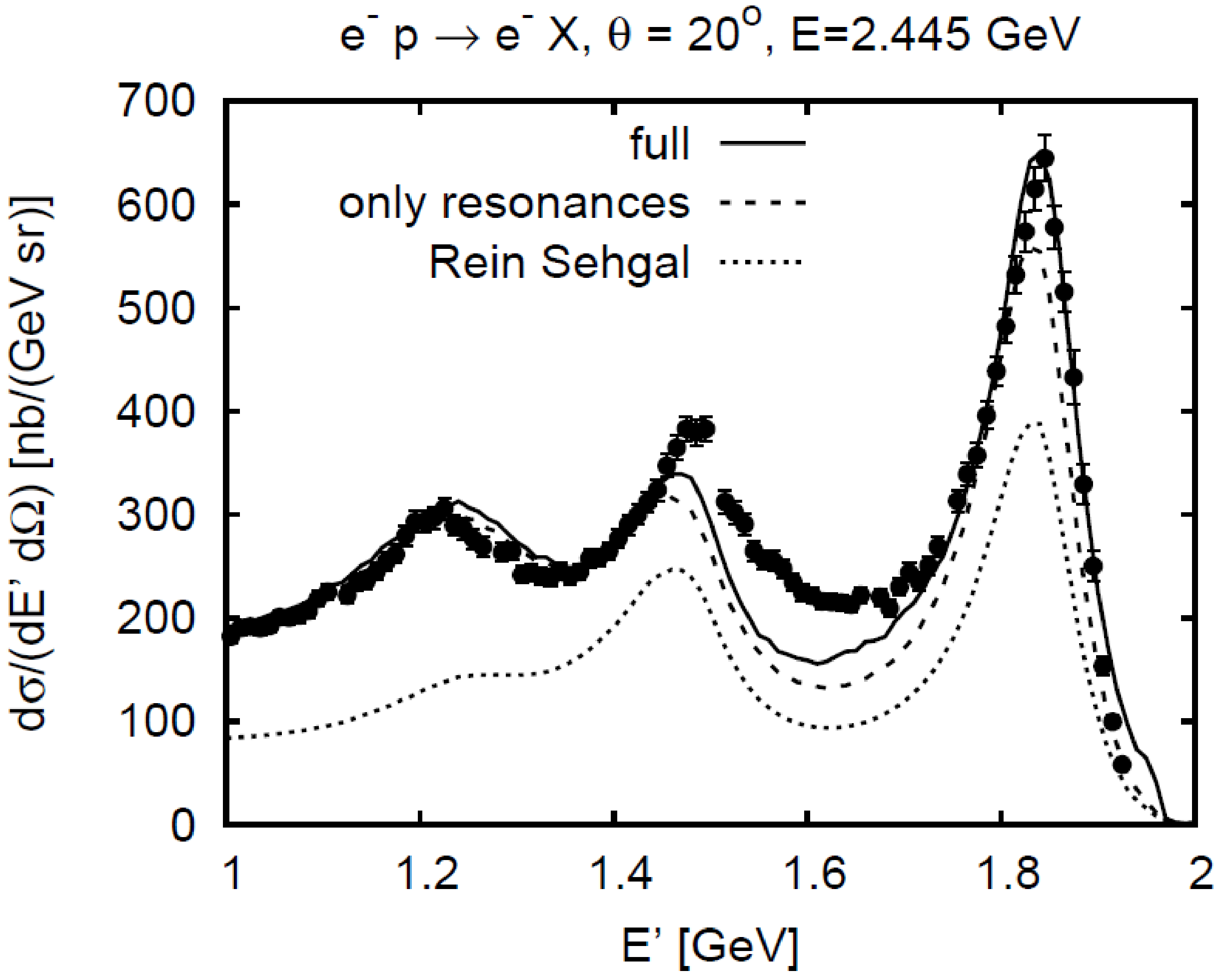
  - Form factors $\Leftrightarrow$ Helicity amplitudes ($A_{1/2}$, $A_{3/2}$, $S_{1/2}$)

1π production

- Elementary process: $\nu_l \, N \rightarrow l \, \pi \, N'$
  - Dominated by resonance production
  - Rein-Sehgal model: Rein-Sehgal, Ann. Phys. 133 (1981) 79.
    - Used by almost all MC generators
    - Relativistic quark model of Feynman-Kislinger-Ravndal with SU(6) spin-flavor symmetry
    - Helicity amplitudes for 18 baryon resonances
    - Lepton mass = 0
      - Corrections: Kuzmin et al., Mod. Phys. Lett. A19 (2004)
        Berger, Sehgal, PRD 76 (2007)
        Graczyk, Sobczyk, PRD 77 (2008)
    - Poor description of π electroproduction data on p

1π production

- Elementary process: $\nu_l \, N \rightarrow l \, \pi \, N'$
  - Dominated by resonance production



.981) 79.

Ravndal with SU(6) spin-

A19 (2004)

8)

- Poor description of π electroproduction data on p

1π production

- N-Δ transition current

$$J^\mu = \bar{\psi}_\mu \left[\left(\frac{C_3^V}{M}(g^{\beta\mu} \not{q} - q^\beta \gamma^\mu) + \frac{C_4^V}{M^2}(g^{\beta\mu} q \cdot p' - q^\beta p'^\mu) + \frac{C_5^V}{M^2}(g^{\beta\mu} q \cdot p - q^\beta p^\mu) \right) \gamma_5 \right.$$

$$\left. + \frac{C_3^A}{M}(g^{\beta\mu} \not{q} - q^\beta \gamma^\mu) + \frac{C_4^A}{M^2}(g^{\beta\mu} q \cdot p' - q^\beta p'^\mu) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2} q^\beta q^\mu \right] u$$

- Helicity amplitudes can be extracted from data on π photo- and electro-production
  - Unitary isobar model MAID Drechsel, Kamalov, Tiator, EPJA 34 (2007) 69
    - Uses world data
    - for all 4 star resonances with W<2 GeV
  - Unitary isobar model+Regge-pole BG at high energies I. Aznauryan, PRC67
  - Dispersion relations
    - CLAS (JLab) data
    - 1st and 2nd resonance regions: Δ(1232), N*(1440), N*(1520), N*(1535)

1π production

- N-Δ transition current

$$J^\mu = \bar{\psi}_\mu \left[\left(\frac{C_3^V}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^V}{M^2}(g^{\beta\mu}q\cdot p' - q^\beta p'^\mu) + \frac{C_5^V}{M^2}(g^{\beta\mu}q\cdot p - q^\beta p^\mu) \right)\gamma_5 \right.$$
$$\left. + \frac{C_3^A}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^A}{M^2}(g^{\beta\mu}q\cdot p' - q^\beta p'^\mu) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2}q^\beta q^\mu \right] u$$

- Axial form factors

$$C_6^A = C_5^A \frac{M^2}{m_\pi^2 + Q^2} \leftarrow \text{PCAC}$$

$$C_4^A = -\frac{1}{4}C_5^A \quad C_3^A = 0 \leftarrow \text{Adler model}$$

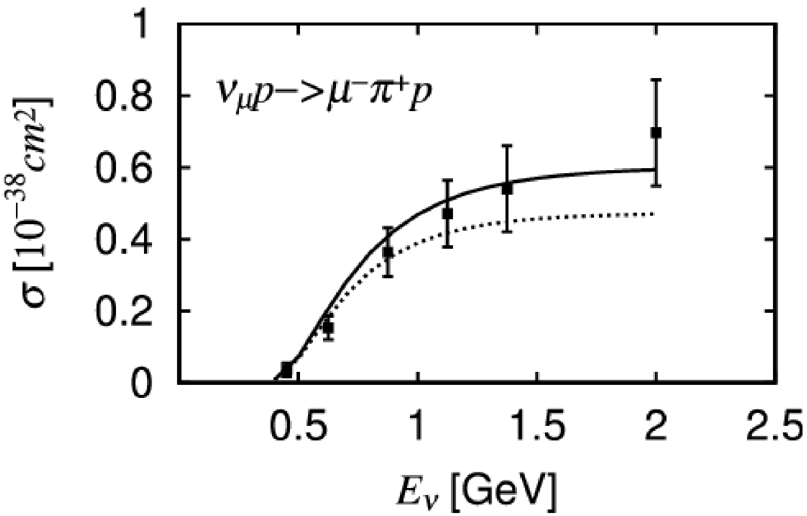
$$C_5^A = C_5^A(0)\left(1 + \frac{Q^2}{M_{A\Delta}^2}\right)^{-1}$$

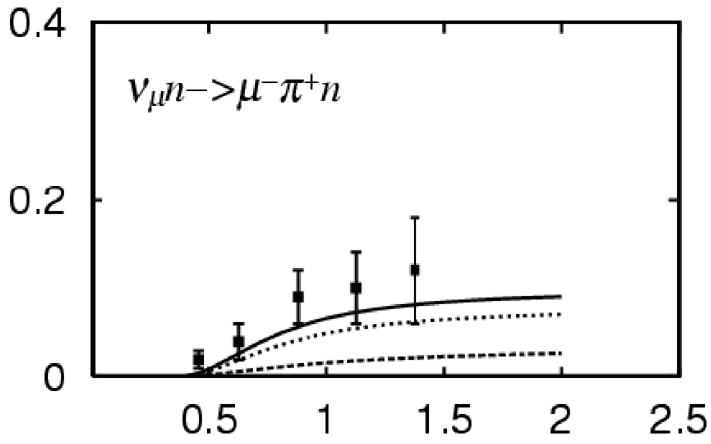
1π production

- N-Δ axial form factors: determination of $C^A_5(0)$ and $M_{A\,\Delta}$
  - $C_5^A(0) = \frac{g_{\Delta N\pi} f_\pi}{\sqrt{6} M} \approx 1.2 \leftarrow$ off diagonal GT relation
  - From ANL and BNL data on $\nu_\mu \, d \to \mu^- \, \pi^+ \, p \, n$
    - with large normalization (flux) uncertainties
  - Graczyk et al., PRD 80 (2009)
    - Deuteron effects
    - Non-resonant background absent
    - $C^A_5(0) = 1.19 \pm 0.08$, $M_{A\,\Delta} = 0.94 \pm 0.03$ GeV
  - Hernandez et al., PRD 81 (2010)
    - Deuteron effects
    - Non-resonant background fixed by chiral symmetry
    - $C^A_5(0) = 1.00 \pm 0.11$ GeV, $M_{A\,\Delta} = 0.93 \pm 0.07$ GeV
    - 20 % reduction of the GT relation

1π production

- Elementary process
  - Sato & Lee model Sato, Uno, Lee, PRC 67 (2003)
  - Dynamical model for π production with γ, e, ν
  - Starting with an effective H: πN, ΔN $\Rightarrow$
  - T-matrix obtained from coupled channel Lippman-Schwinger eq.
  - Good agreement with data





  - Bare ΔN renormalized by meson clouds (30 %): $C^A_5(0)$ =0.96 GeV reconciles the empirical value with quark model results

1π production

- Incoherent 1π production in nuclei
  - Large number of excited states $\Rightarrow$ semiclassical treatment
  - π propagation (scattering, charge exchange), absorption (FSI)
  - Most models cannot calculate this reaction channel.

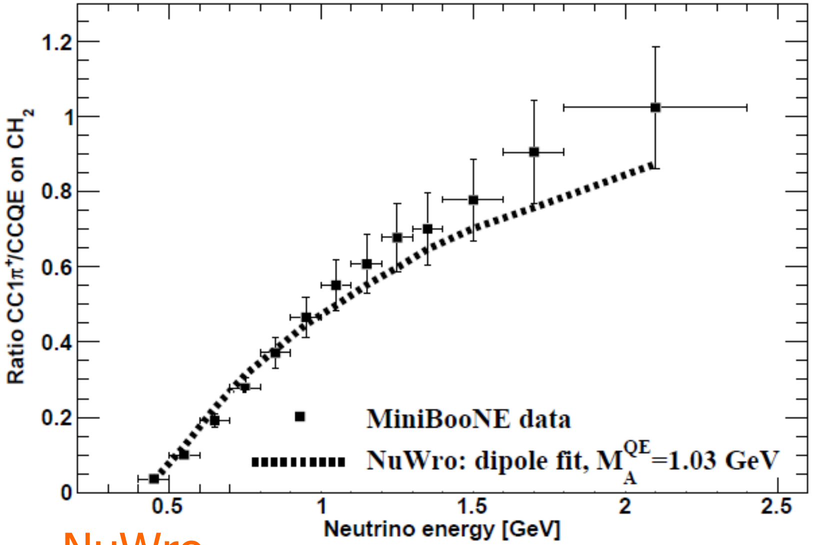
    Exceptions:
    - MC generators: NUANCE, NEUT, GENIE, NuWro
    - Cascade: Ahmad et al., PRD 74 (2006)
    - Transport: GiBUU

1π production

- Incoherent 1π production in nuclei (FSI)
  - NuWro J. Sobczyk et al.
    - Intranuclear cascade
    - π propagation: empirical π-N vacuum σ
    - π absorption: π-A absorption data
  - Ahmad et al., PRD 74 (2006)
    - Cascade (~NuWro)
    - In-medium modification of Δ spectral f. (only in the production)
  - GiBUU
    - Transport: one approach for eA, νA, pA, πA reactions
    - π, N but also Δ are propagated
    - Main absorption mech.: Δ N $\rightarrow$ N N, π N N $\rightarrow$ N N

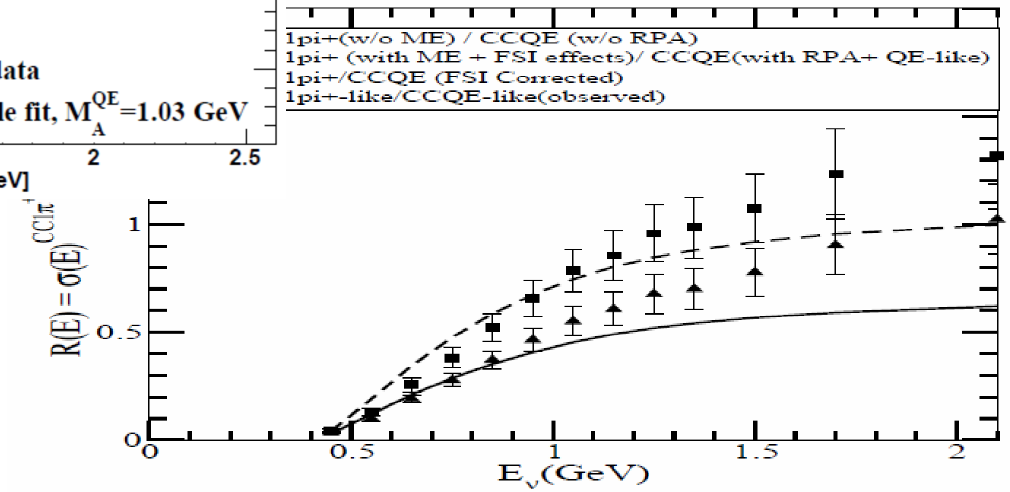
1π production

- Comparison to the $\sigma(CC\pi^+)/\sigma(\text{CCQE-like})$ ratio at MiniBooNE

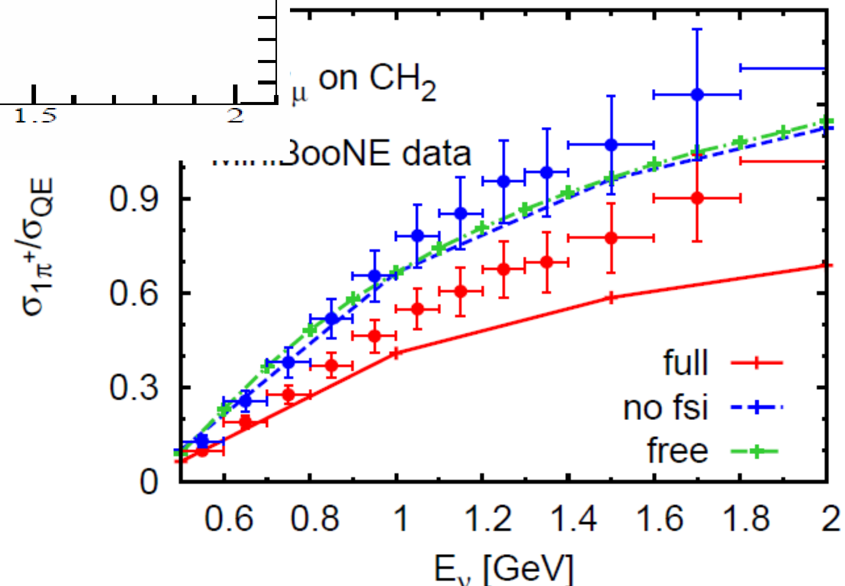


NuWro

Athar et al.



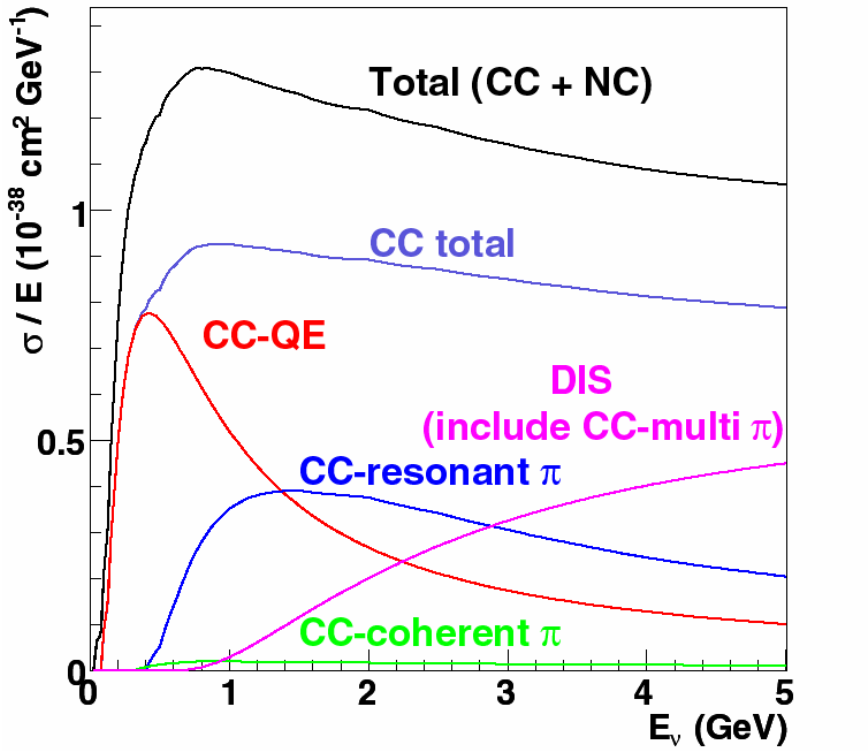
GiBUU



1π production

- Coherent pion production
  - CC $\nu_l \, A \rightarrow l^- \, \pi^+ \, A$
  - NC $\nu \, A \rightarrow \nu \, \pi^0 \, A$
    - Takes place at low q^2
    - Very small cross section
    - At $q^2 \sim 0$, axial current not suppressed

NEUT
Hiraide@NuInt09



1π production

- Coherent pion production models
  - PCAC — Rein & Sehgal NPB 223 (83) 29; Berger & Sehgal, PRD 76 (2007),79 (2009); Paschos & Schalla, PRD 80 (2009),
    - In the $q^2=0$ limit, PCAC is used to relate ν induced coherent pion production to πA elastic scattering
    - Extrapolated to $q^2 \neq 0$
    - R&S: describe πA in terms of πN scattering
    - B&S, P&S: use πA data
  - Problems: Hernandez et al., PRD 80 (2009) 013003
    - $q^2=0$ limit neglects important angular dependence at low energies
    - R&S: The πA elastic description is not realistic
    - B&S,P&S: spurious initial π distortion present in πA but not in cohπ

1π production

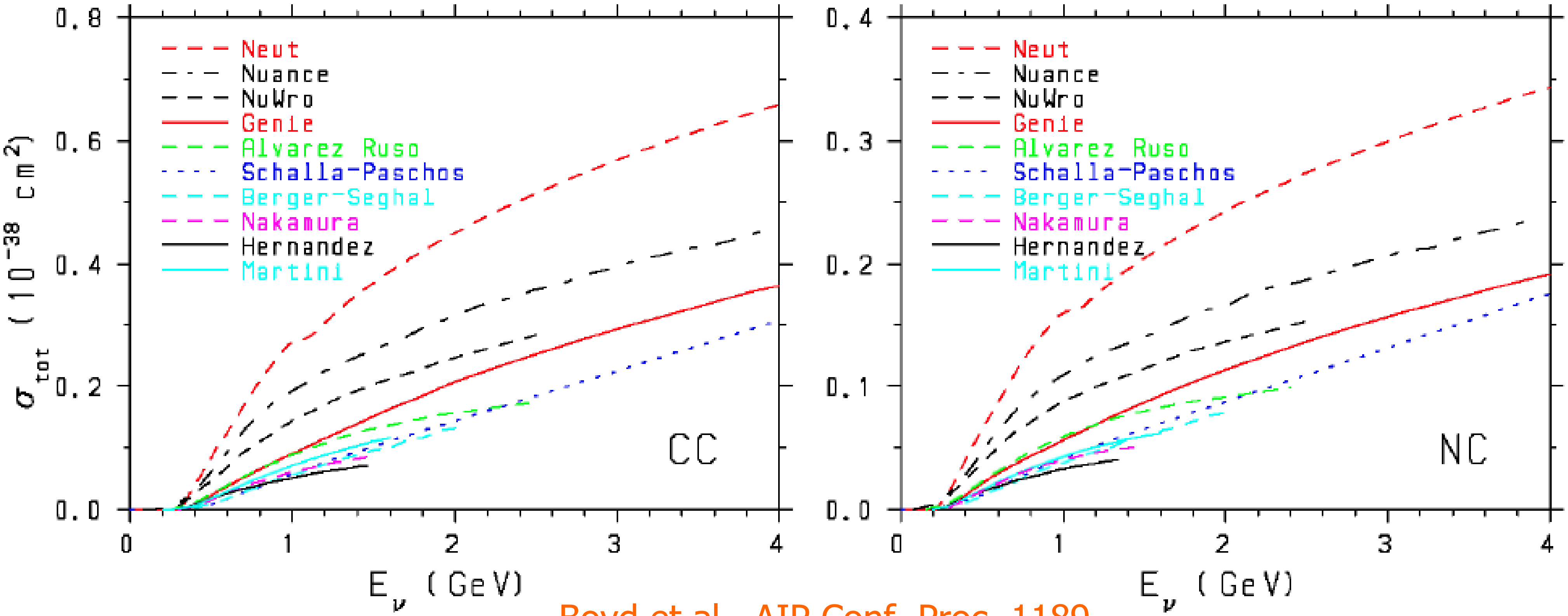
- Coherent pion production models
  - PCAC
    Rein & Sehgal NPB 223 (83) 29
    Berger & Sehgal, PRD 76 (2007),79 (2009)
    Paschos & Schalla, PRD 80 (2009),
    - In the $q^2=0$ limit, PCAC is used to relate ν induced coherent pion production to πA elastic scattering
    - Extrapolated to $q^2 \neq 0$
    - R&S: describe πA in terms of πN scattering
    - B&S, P&S: use πA data
  - Problems of PCAC models: less relevant as the energy increases
    - NOMAD: $\sigma=72.6 \pm 8.1(\text{stat}) \pm 6.9(\text{syst}) \times 10^{-40}$ cm^2
    - Consistent with RS: $\sigma \approx 78 \times 10^{-40}$ cm^2

1π production

- Coherent pion production
  - Microscopic models: Singh et al., PRL 96 (2006)
    LAR et al, PRC 76 (2007)
    Amaro et al., PRD 79 (2009)
    Nakamura et al., PRC 81 (2010)
    - Δ excitation is dominant
    - Δ properties change in the nuclear medium
    - π distortion: DWIA with optical potential based on Δ-hole model
    - Treatment is consistent with incoherent π production
    - Valid only at low energies
    - $\sigma \sim \left[C_5^A(0)\right]^2$

1π production

- Coherent pion production

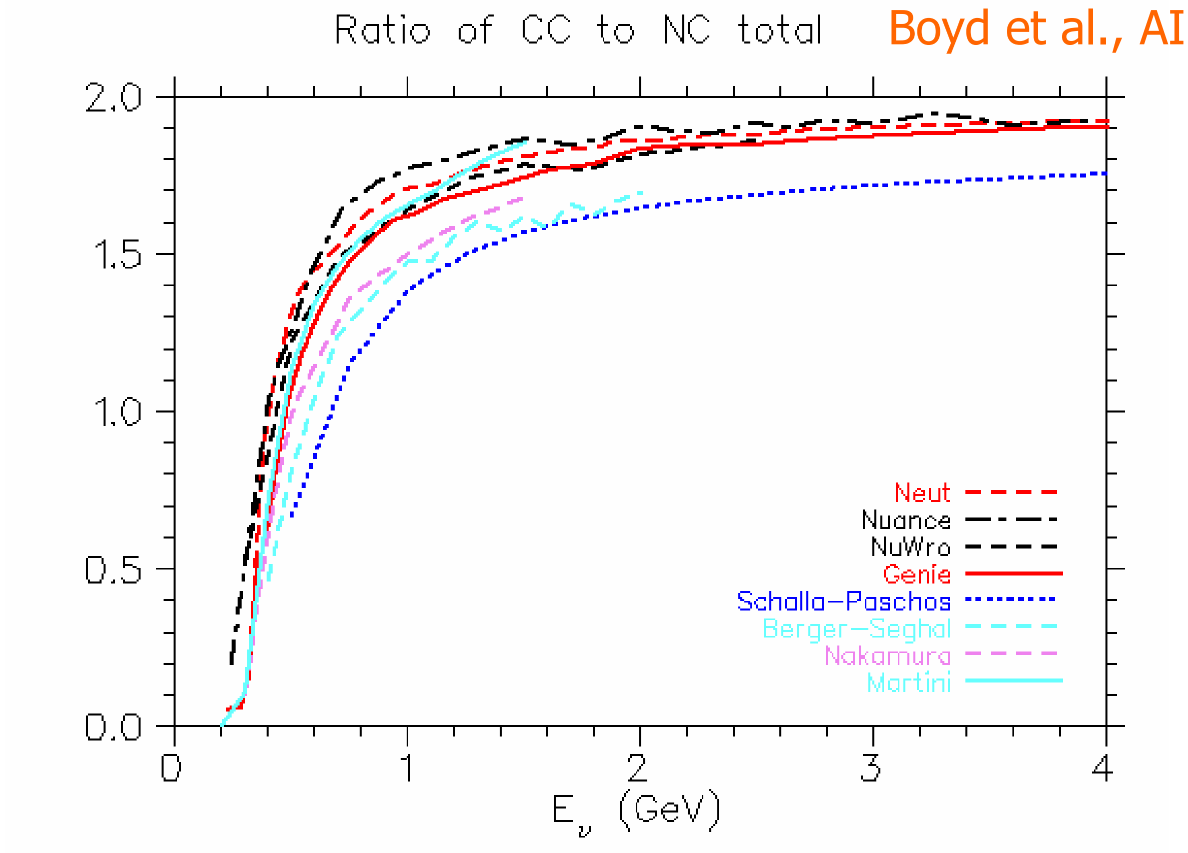


Boyd et al., AIP Conf. Proc. 1189

1π production

- Coherent pion production

Boyd et al., AIP Conf. Proc. 1189



- SciBooNE: PRD 81 (2010)
- NC π^o σ compatible with R&S
- $CC\pi^+/NC\pi^o = 0.14^{+0.30}_{-0.28}$
- Theoretical models predict $CC\pi^+/NC\pi^o \sim$ 1-2 !

Conclusions

- In spite of the exp. and th. effort basic νA interaction mechanisms (QE, 1π) are not understood
- Comparison to inclusive data is needed
- Look forward to new data and theoretical progress