Present status of ν cross sections

Luis Alvarez Ruso

Introduction

- Neutrino interactions with matter are at the heart many interesting and physical processes: astrophysics, BSM, hadronic & nuclear physics
- Oscillation experiments (with accelerator ν in the few-GeV region): T2K, NOvA, MicroBooNE, Hyper-K,
  - Goals: ν mass hierarchy, CP violation
  - Good understanding of neutrino interactions are crucial for:
    - ν detection, flavor identification
    - reduction of systematic errors
      - E_ν reconstruction, ν flux calibration
      - determination of (irreducible) backgrounds

e.g. $\nu_l\, N \rightarrow \nu_l\, \pi^0\, N'$ in $\nu_\mu \rightarrow \nu_e$ searches

$\nu_l\, N \rightarrow \nu_l\, \gamma\, N'$

Introduction

- Near detectors help to reduce systematic errors:

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

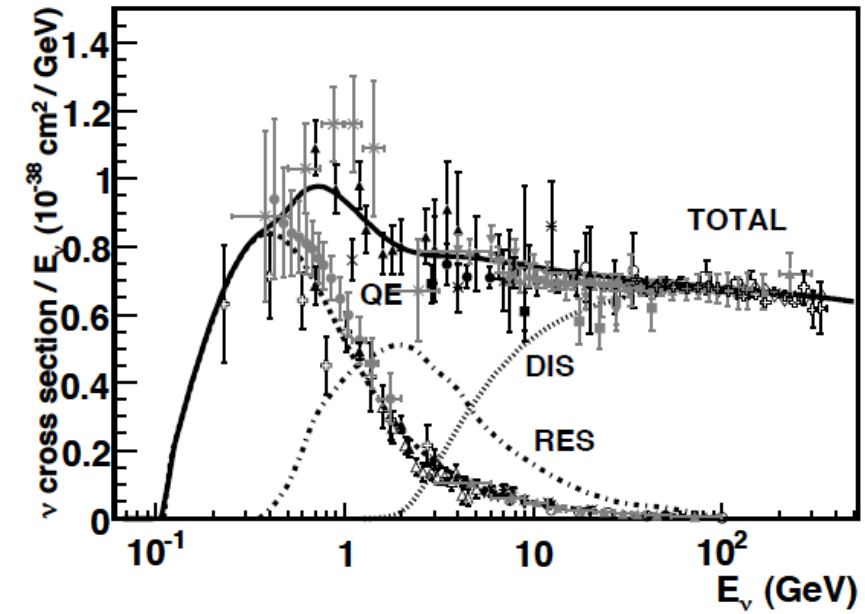
F. Sanchez @ NuPhys2015

but c.s. uncertainties do not cancel (exactly) in the ratio

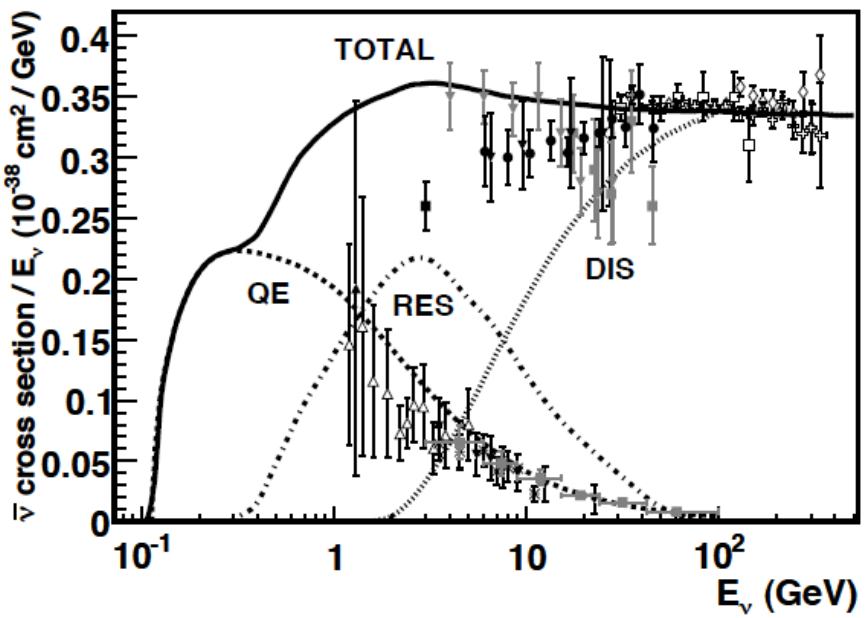
  - exposed to different fluxes with different flavor composition
  - different geometry, acceptance and targets

- Neutrino-nucleus c.s. mismodeling could lead to unacceptably large systematic uncertainties or biased measurements
- Precision of 1-5% in ν cross sections might be required

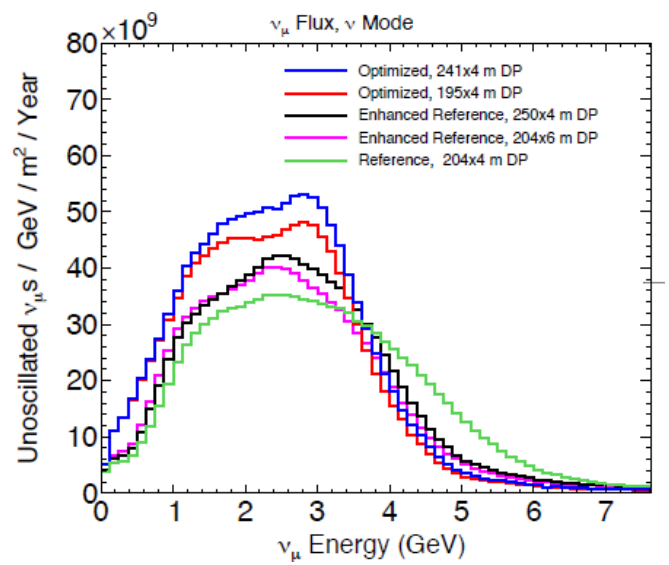
Introduction



CC cross sections:
world data and NUANCE generator
Formaggio, Zeller, Rev. Mod. Phys. (2012)

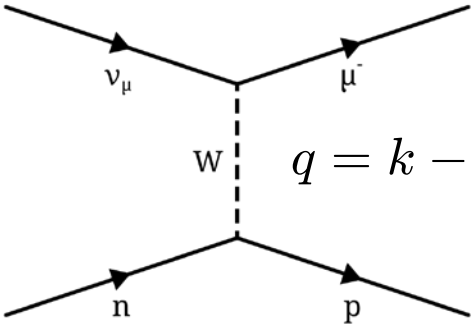


DUNE flux



ν QE scattering on the nucleon

$$\begin{aligned}
\text{CCQE}: \nu(k) + n(p) &\rightarrow l^-(k') + p(p') \\
\bar{\nu}(k) + p(p) &\rightarrow l^+(k') + n(p') \\
\text{NCE}: \nu(k) + N(p) &\rightarrow \nu(k') + N(p') \\
\bar{\nu}(k) + N(p) &\rightarrow \bar{\nu}(k') + N(p')
\end{aligned}$$



$$q = k - k' = p' - p$$

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

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

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

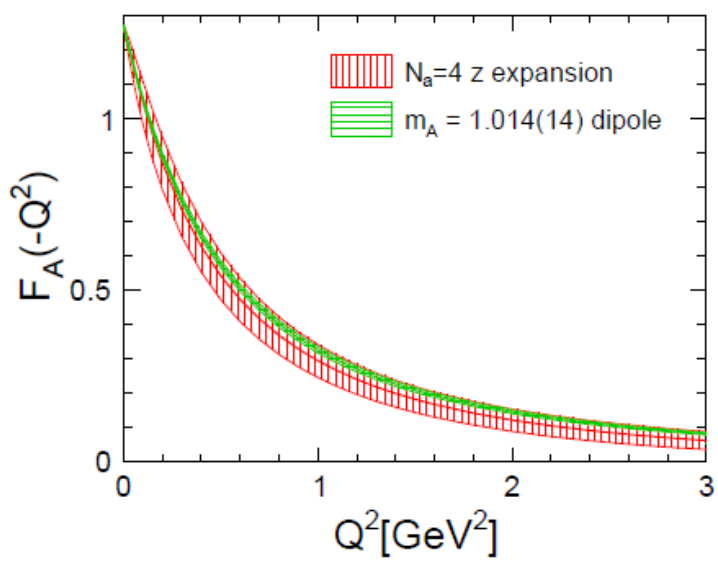
QE scattering on the nucleon

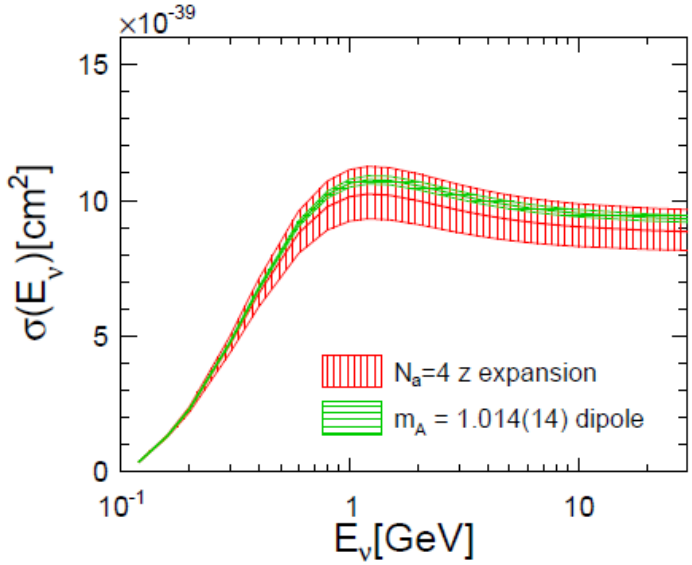
- Dipole ansatz:

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

  - Not theoretically justified
  - Leads to artificially small errors in M_A

- z-expansion Meyer et al., PRD 93 (2016) : Fit to ANL, BNL, FNAL data

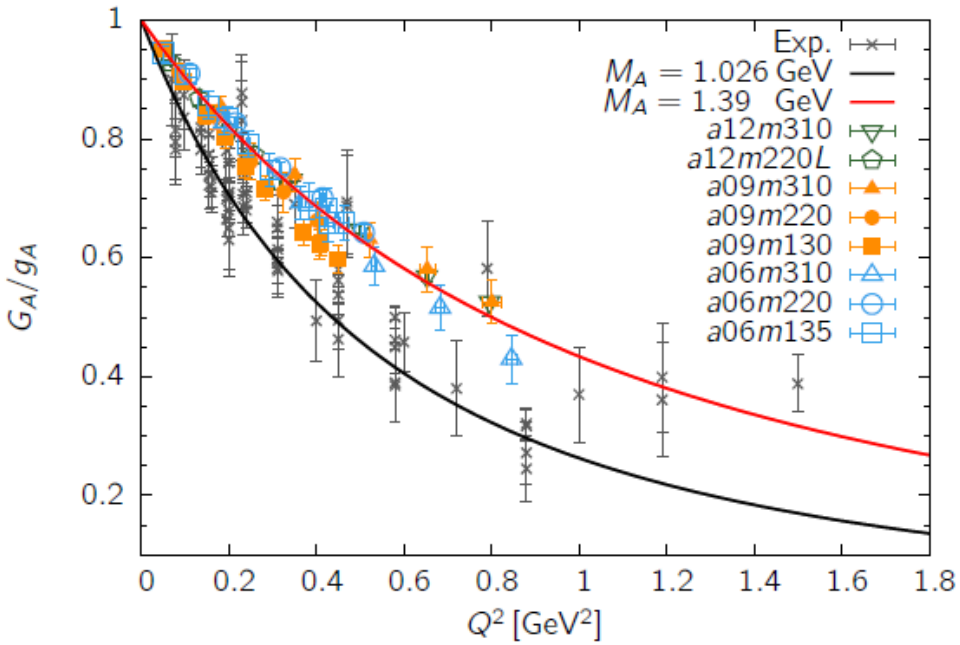




  - $\langle r_A^2 \rangle$ = 0.46(22) fm² vs 0.453(12) fm² Bodek et al., EPJC 53 (2008)

F_A & lQCD

- More precise information about F_A
  - Lattice QCD



Gupta et al., arXiv:1705.06834

  - M_A = 1.39 GeV ⇔ $\langle r_A^2 \rangle$ =0.24 fm^2
  - New CCQE measurements on D/H target
  - Modern data? heavier targets: $CH_{1,2}$, H_2O, ^{40}Ar, ^{56}Fe

CCQE on nuclear targets

- 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 $P_{\mathrm{Pauli}} = 1 - \Theta(p_F - |\vec{p}|)$
  - Average binding energy $E = \sqrt{\vec{p}^2 + m_N^2} - \epsilon_B$
  - Explains the main features of the (e,e') inclusive c.s in the QE region
  - Fails in the details (nuclear dynamics needed)

CCQE on nuclear targets

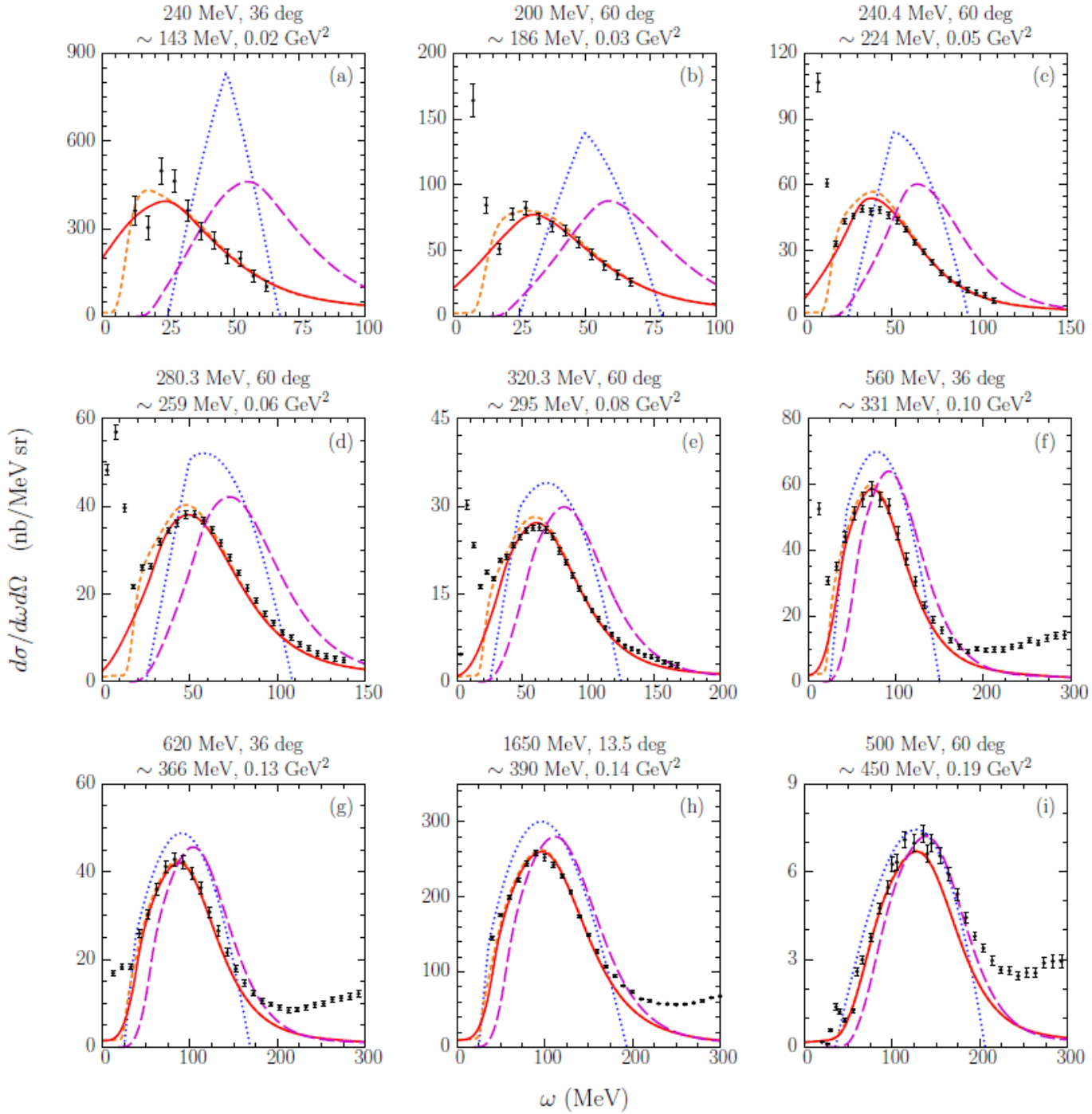
- Spectral functions

$$
\begin{aligned}
D(p) &= (\not{p} + M)G(p) \\
G(p) &= \frac{1}{p^0 + E_p - i\epsilon}\left[\int_{-\infty}^{\mu} \frac{\mathcal{A}_h(\omega,\vec{p})}{p^0 - \omega - i\epsilon} d\omega + \int_{\mu}^{\infty} \frac{\mathcal{A}_p(\omega,\vec{p})}{p^0 - \omega + i\epsilon} d\omega\right]
\end{aligned}
$$

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

- ImΣ = 0 $\Rightarrow$ mean-field approximation

ets



$$\frac{\mathbf{l}_p(\omega,\vec{p})}{-\omega+i\epsilon}d\omega\Big]$$

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

Ankowski et al., PRD91 (2015)

CCQE on nuclear targets

- Spectral functions

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

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

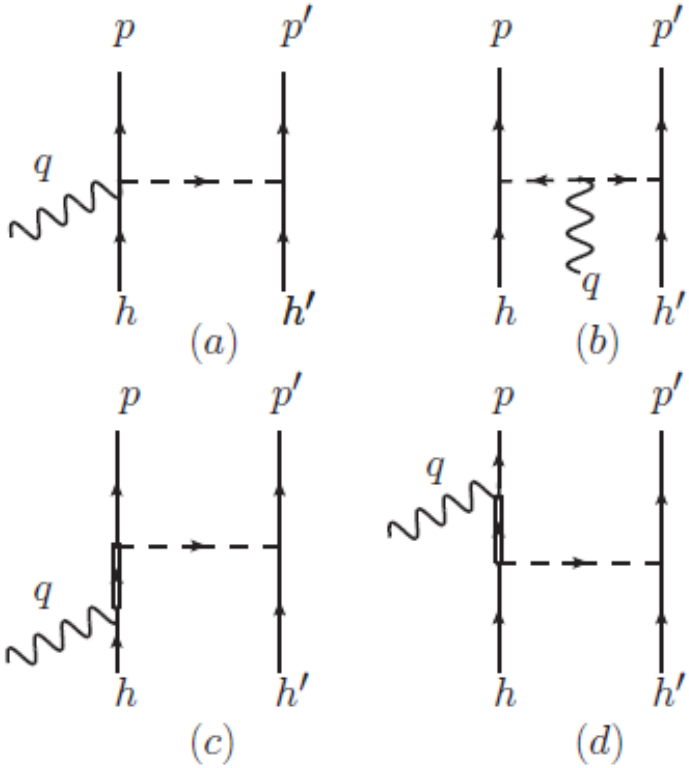
$$\mathcal{A}_{p,h}(p) = \mp \frac{1}{\pi} \frac{\mathrm{Im}\Sigma(p)}{[p^2 - M^2 - \mathrm{Re}\Sigma(p)]^2 + [\mathrm{Im}\Sigma(p)]^2}$$

  - ImΣ = 0 $\Rightarrow$ mean-field approximation

- Significant improvement in the description of the (e,e') c.s.
- Formalism applicable to inelastic inclusive scattering
- Realistic spectral fuctions are not available for heavier nuclei (like Ar)

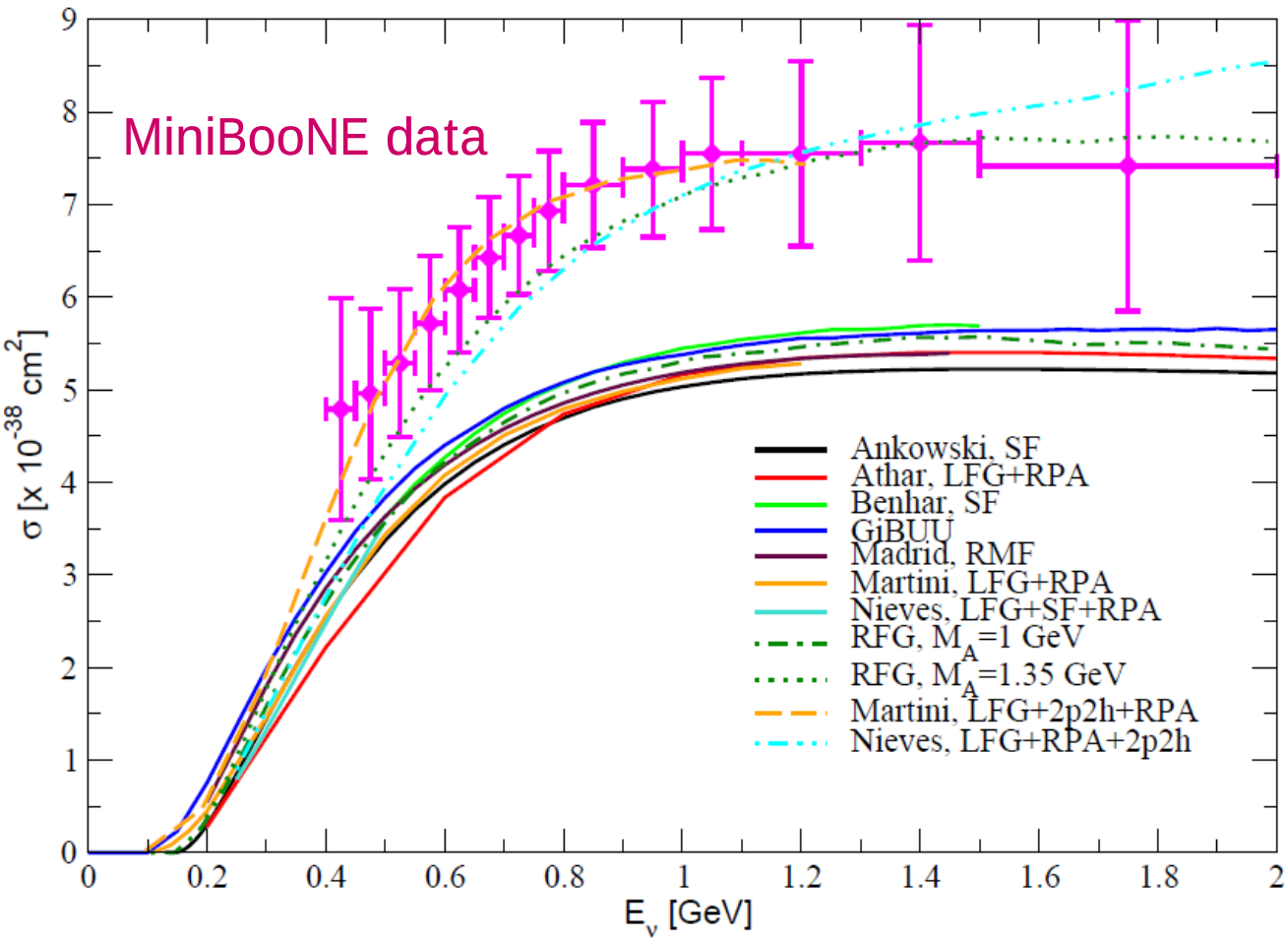
CCQE-like on nuclear targets

- Two-nucleon (2p2h) contributions:



CCQE-like on nuclear targets

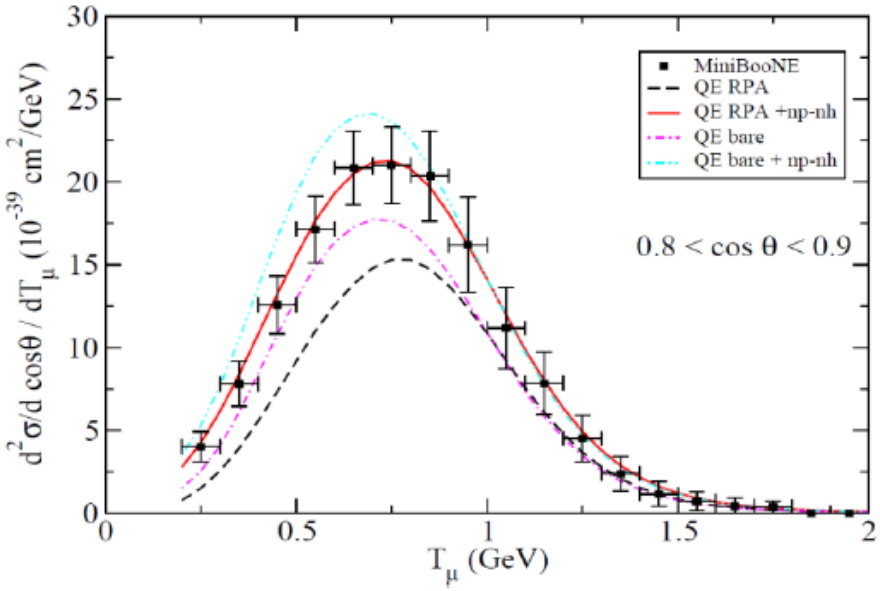
MiniBooNE puzzle (2009): CCQE on ^{12}C



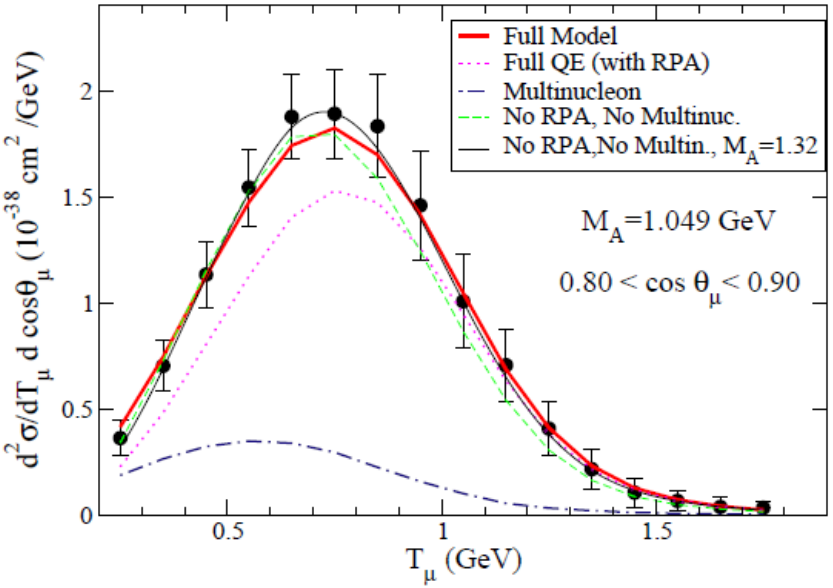
CCQE-like on nuclear targets

- Two-nucleon (2p2h) contributions:
  - Martini et al., PRC 80 (2009)
  - Nieves et al., PRC 83 (2011)
  - Amaro et al., PLB 696 (2011)

Martini et al.

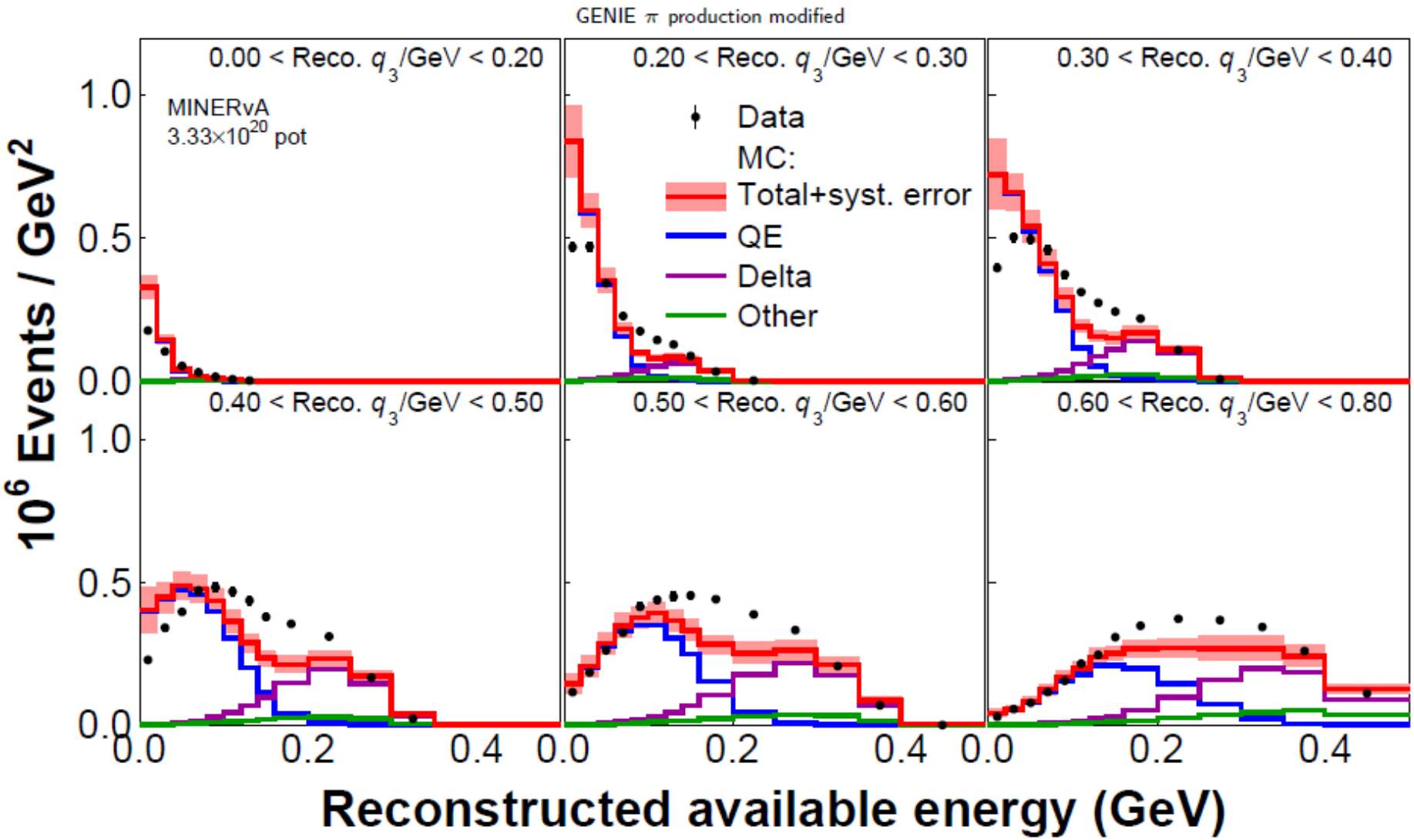


Nieves et al.



- Unsubtracted CCQE-like events alter E_ν reconstruction, influencing oscillation analyses Lalakulich, Mosel, PRC 86 (2012); Coloma, Huber, PRL 111(2013)

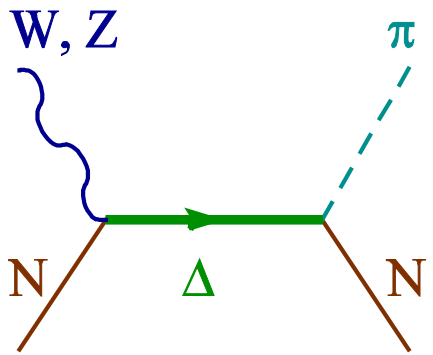
2p2h @ MINERvA



P. Rodrigues @ NuInt 2015, Fermilab W&C

Weak resonance excitation

- Δ (1232) excitation:



- N-Δ transition current:

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

- Vector form factors
  - extracted from data on π photo- and electro-production

Weak resonance excitation

- $\Delta(1232)$ $J^P=3/2^+$

$$J_\alpha = \bar{u}^\mu(p')\left[\left(\frac{C_3^V}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu}q\cdot p - q_\alpha p_\mu)\right)\gamma_5\right.$$
$$\left. + \frac{C_3^A}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2}q_\alpha q_\mu\right] u(p)$$

- Axial form factors

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

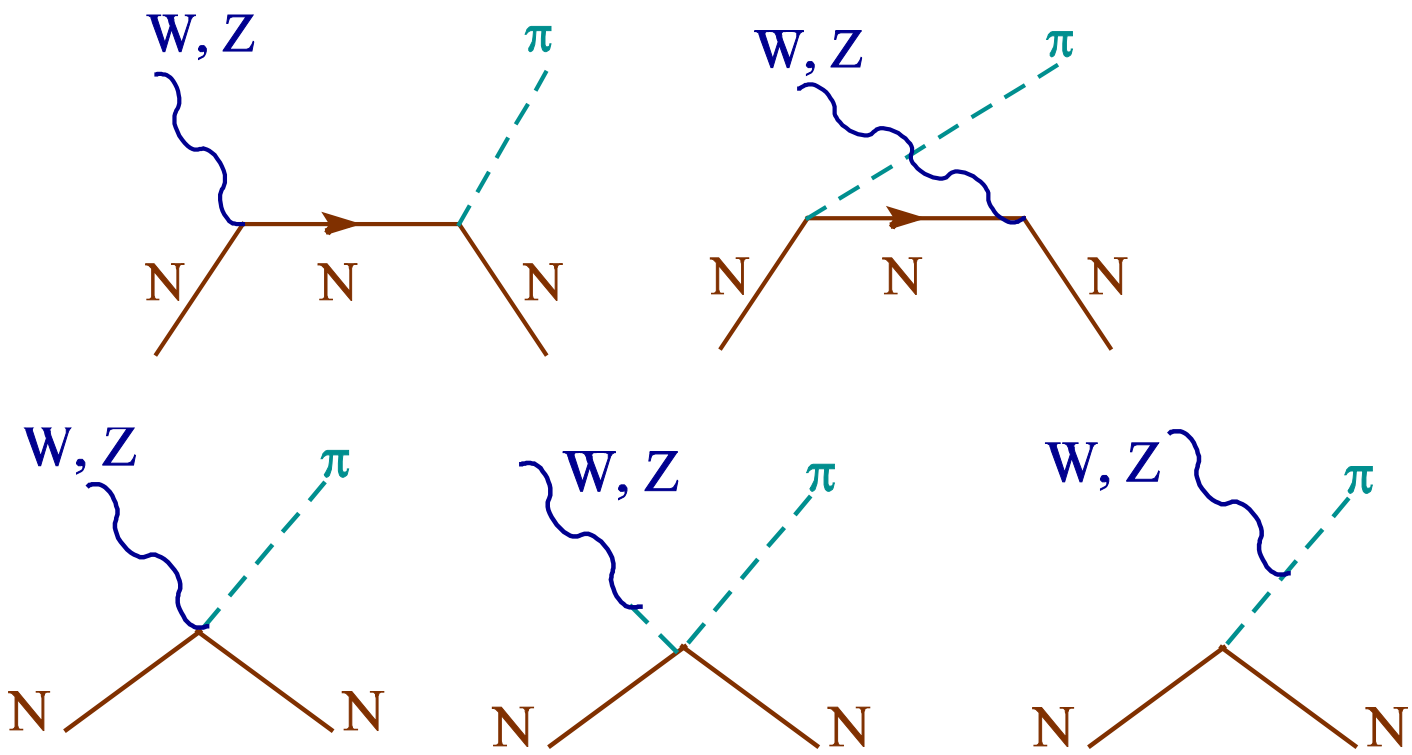
$$C_5^A(0) = \sqrt{\frac{2}{3}}g_{\Delta N\pi} = 1.15 - 1.20 \qquad g_{\Delta N\pi} \Leftrightarrow \Gamma(\Delta \to N\pi)$$

- From ANL and BNL data on $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$
  - $M_{A\,\Delta}$ = 0.96 ± 0.07 GeV LAR, Hernandez, Nieves, PRD (2016)
  - $C^A_{3,4}$: consistent with zero
  - Little (no) sensitivity to heavier baryon resonances

1π production on the nucleon

$$\nu_l \, N \rightarrow l \, \pi \, N'$$

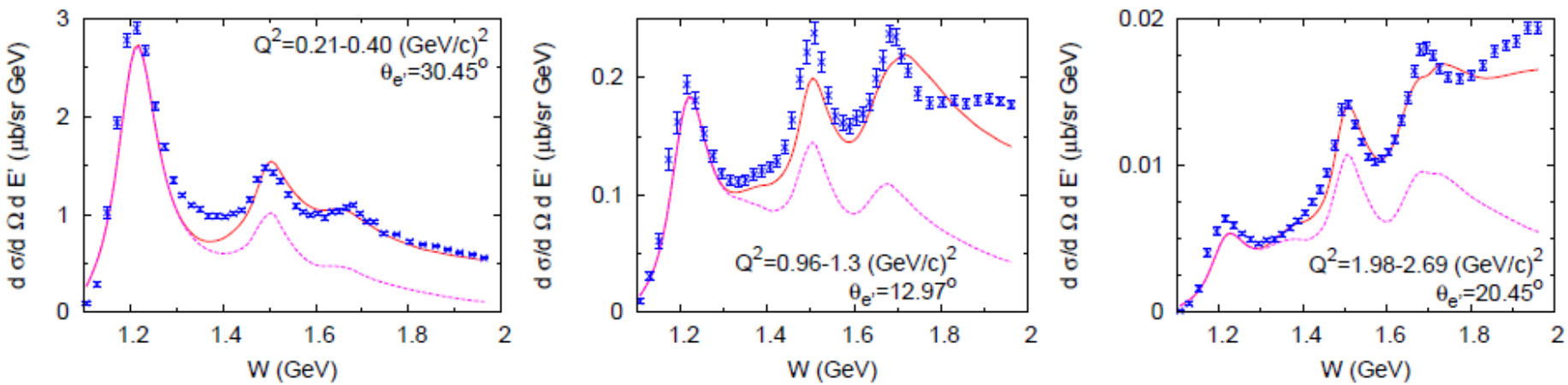
- From Chiral symmetry:



Hernandez et al., Phys.Rev. D76 (2007) 033005

Weak meson production

- Strategy:
  - Resonant + non-resonant amplitudes added coherently
  - Unitarization (in coupled channels)
  - Consistency with πN and $\gamma(^*)$N reactions
- E.g.: Dynamical Coupled Channel (DCC) Model Nakamura et al., PRD92 (2015)
  - Based on a combined analysis of πN, $\gamma(^*)$N $\rightarrow$ πN, ηN, KΛ, KΣ



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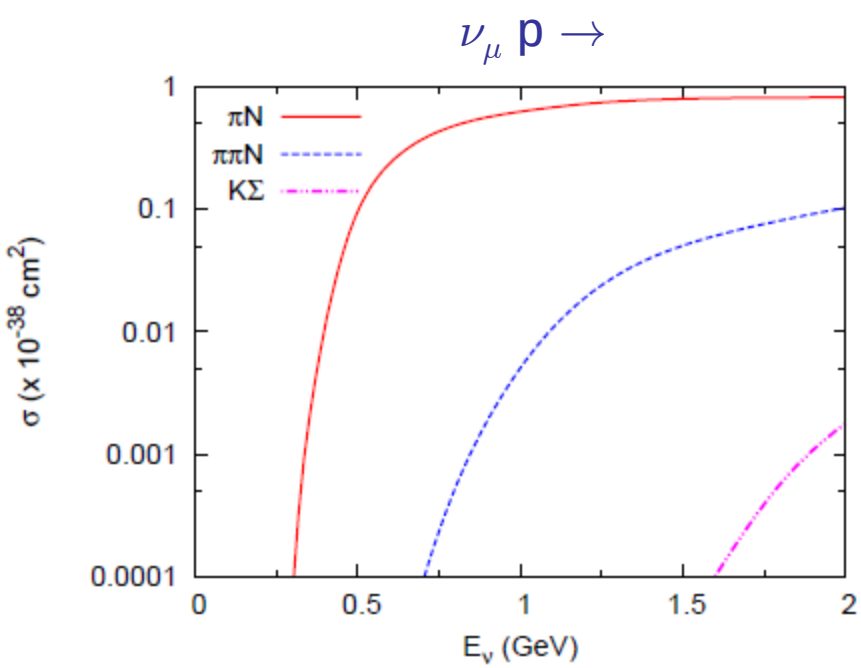
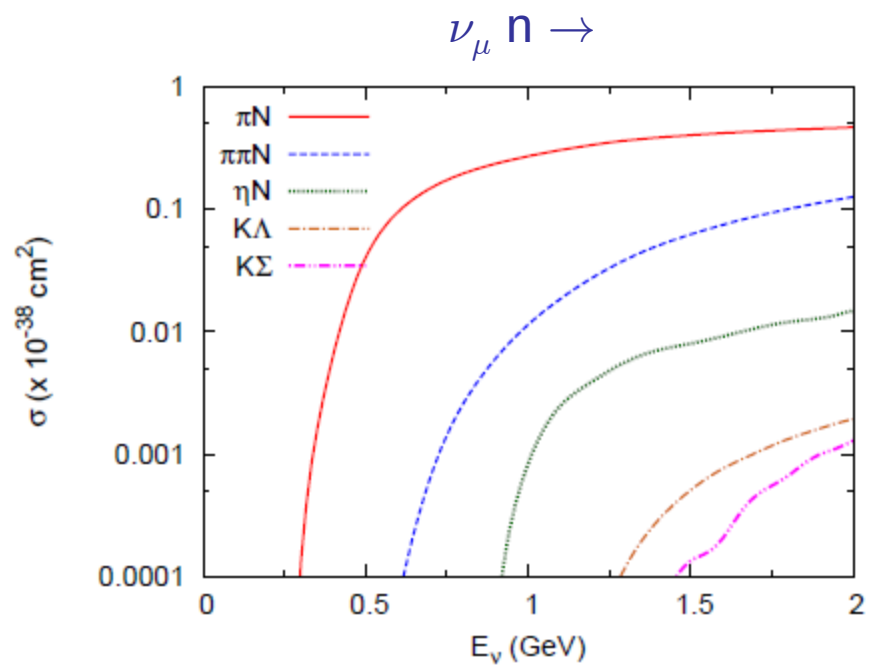
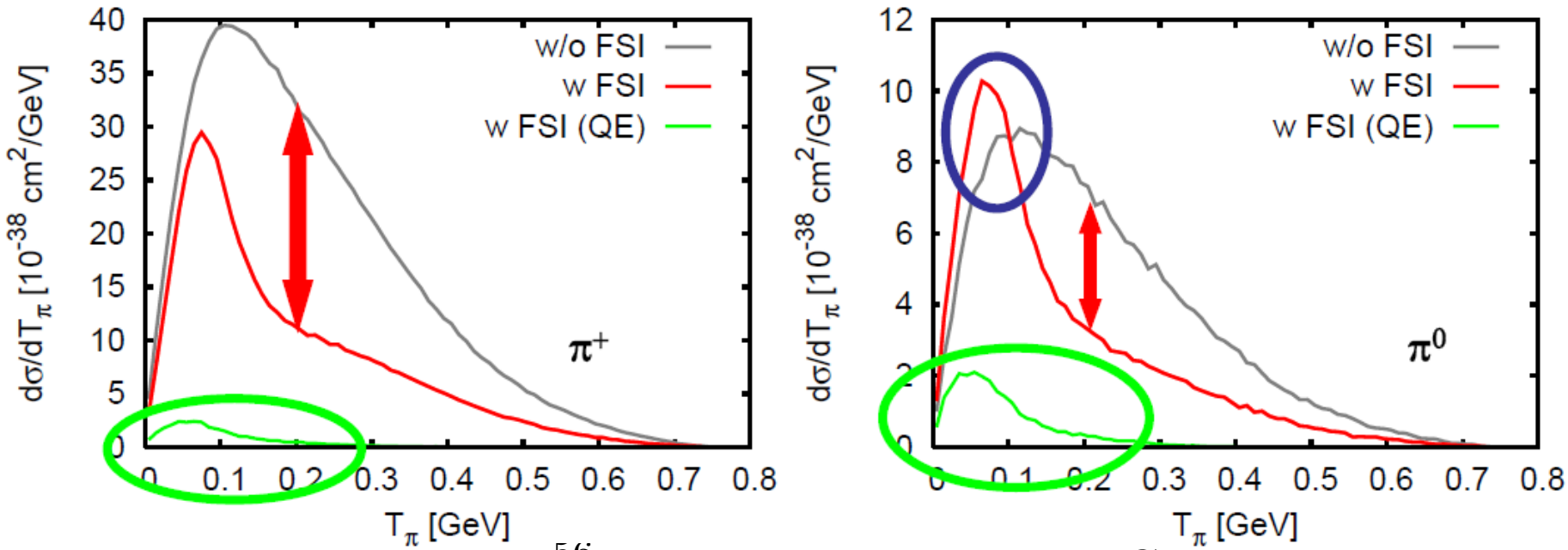




1π production on nuclei

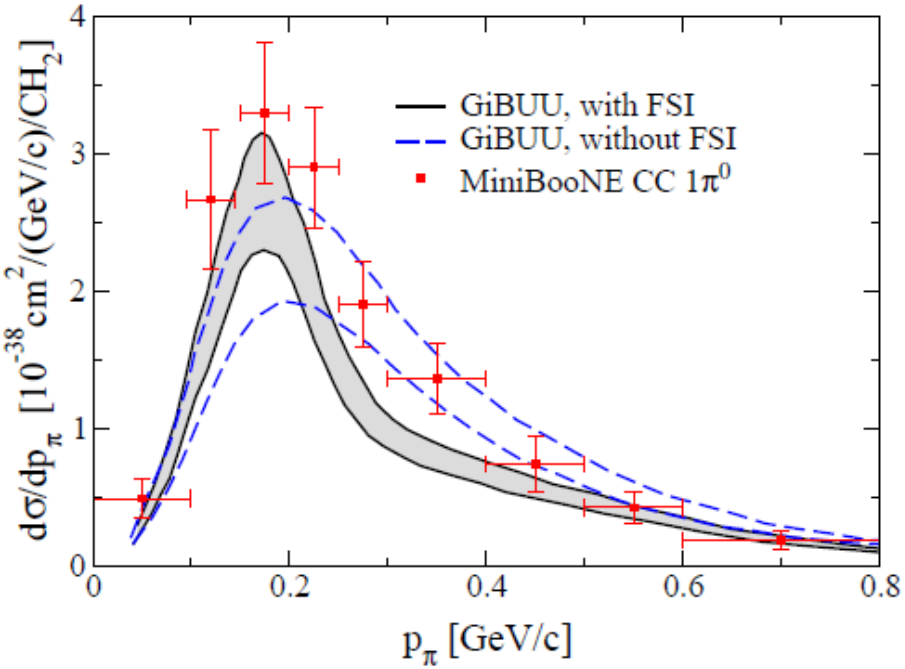
- GiBUU Leitner, LAR, Mosel, PRC 73 (2006)
  - Effects of FSI on pion kinetic energy spectra
    - strong absorption in Δ region
    - side-feeding from dominant π^+ into π^0 channel
    - secondary pions through FSI of initial QE protons



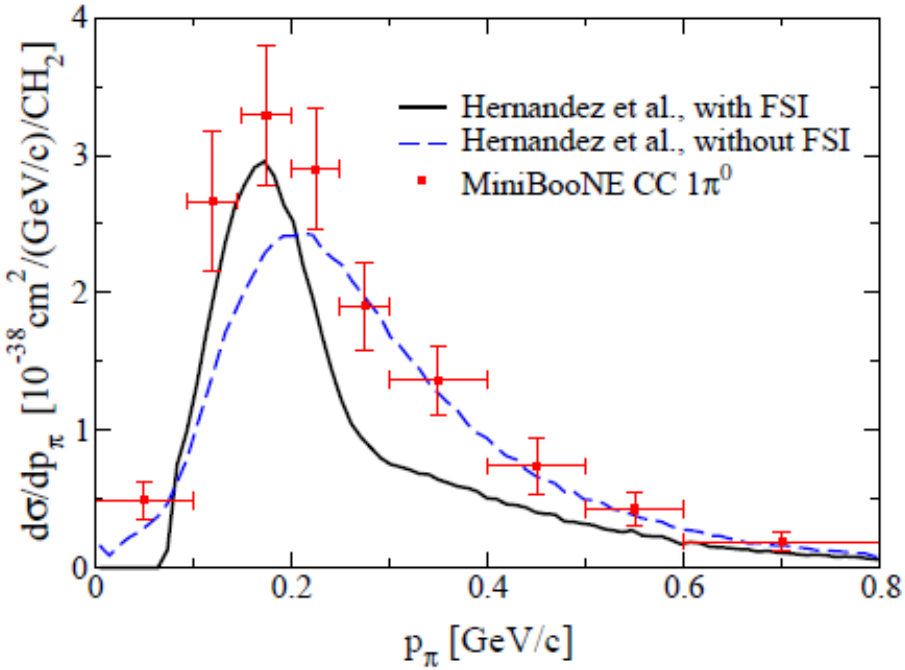
$$\nu_\mu + {}^{56}Fe \to \mu^- \pi X \quad E_\nu = 1 \text{ GeV}$$

1π production on nuclei

- Comparison to MiniBooNE: $CC1\pi^0$ Aguilar-Arevalo, PRD83 (2011)



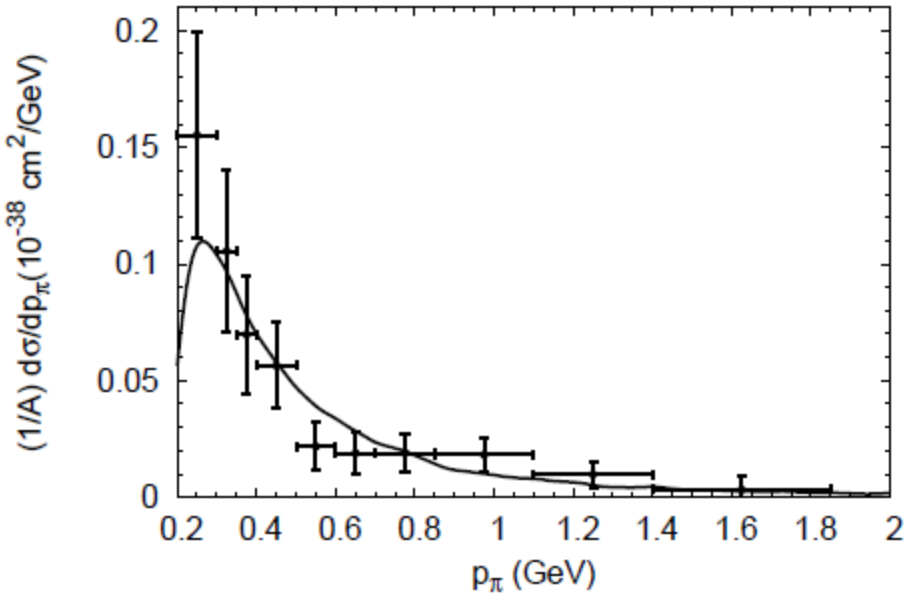
Hernandez et al., PRD87 (2013)



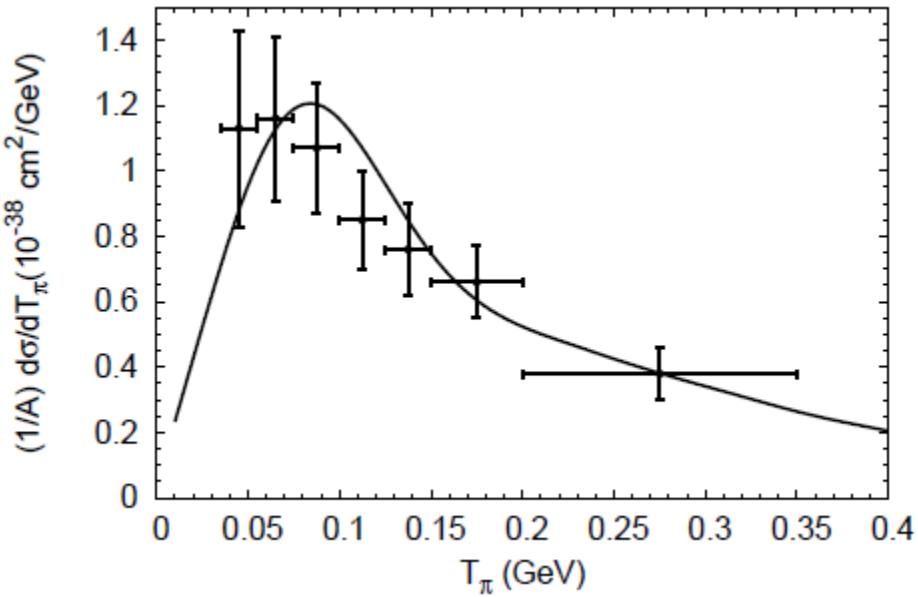
Lalakulich, Mosel, PRC87 (2013)

1π production on nuclei

Comparison to T2K (ND280): $CC\pi^+$
Abe et al., PRD 95 (2017)



Comparison to MINERvA: $CC\pi^\pm$
Eberly et al., PRD 92 (2015)

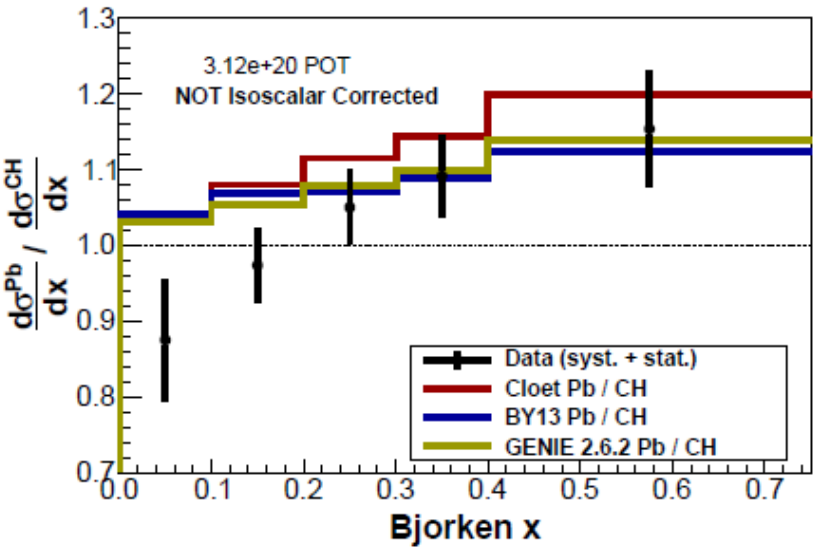


Mosel, Gallmeister, arXiv:1702.04932

DIS

$$W^{\mu\nu} = W_1\left(\frac{q^\mu q^\nu}{q^2} - g^{\mu\nu}\right) + \frac{W_2}{M^2}\left(p^\mu - \frac{p\cdot q}{q^2}q^\mu\right)\left(p^\nu - \frac{p\cdot q}{q^2}q^\nu\right) + W_3 i\epsilon^{\mu\nu\alpha\beta}\frac{p_\alpha q_\beta}{2M^2}$$

- Fits are performed to extract PDF
- Onset of DIS? Usually W>2 GeV, Q^2 > 1 GeV^2
- At low W, Q^2 non-trivial interplay of
  - Higher Twists
  - Nuclear corrections
- MINERvA has observed an unexplained discrepancy in the shadowing region



Mousseau, PRD93

Instead of Conclusions

NuSTEC: Neutrino Scattering Theory Experiment Collaboration

http://nustec.fnal.gov/

NuSTEC White Paper: Status and Challenges of Neutrino-Nucleus Scattering, LAR et al., arXiv:1706.03621