Progress and open questions in the physics of ν interactions with nucleons and nuclei

Luis Alvarez Ruso

Introduction

- Neutrino interactions with matter are at the heart many interesting and relevant physical processes
  - Astrophysics
    - Dynamics of the core-collapse in supernovae
    - r-process nucleosynthesis
  - Physics Beyond the Standard Model
    - Non-standard ν interactions
  - 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
    - Complement electron scattering studies

Introduction

- Neutrino interactions with matter are at the heart of all experiments seeking to unravel its nature.

- Oscillation experiments (with accelerator ν in the few-GeV region)
  - Good understanding of neutrino interactions are important for:
    - ν detection, E_ν reconstruction, ν flux calibration
    - determination of (irreducible) backgrounds
    - reduction of systematic errors
    - needed in the quest for CP violation and ν mass hierarchy
  - Near detectors help to reduce systematic errors but:
  - ND vs FD:
    - exposed to different fluxes with different flavor composition
    - different targets
  - All modern experiments are performed with nuclear targets
    - nuclear effects: essential for the interpretation of the data

Relevance for oscillation experiments

- (Kinematic) E_ν reconstruction via CCQE scattering:

$$\nu_l \, n \to l^- \, p$$
$$\nu_l \, p \to l^+ \, n$$

$$E_\nu = \frac{2m_n E_\mu - m_\mu^2 - m_n^2 + m_p^2}{2(m_n - E_\mu + p_\mu \cos\theta_\mu)}$$

  - Important for oscillations: $P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{23} \, \sin^2 \frac{\Delta m_{23}^2 L}{4E_\nu}$

Relevance for oscillation experiments

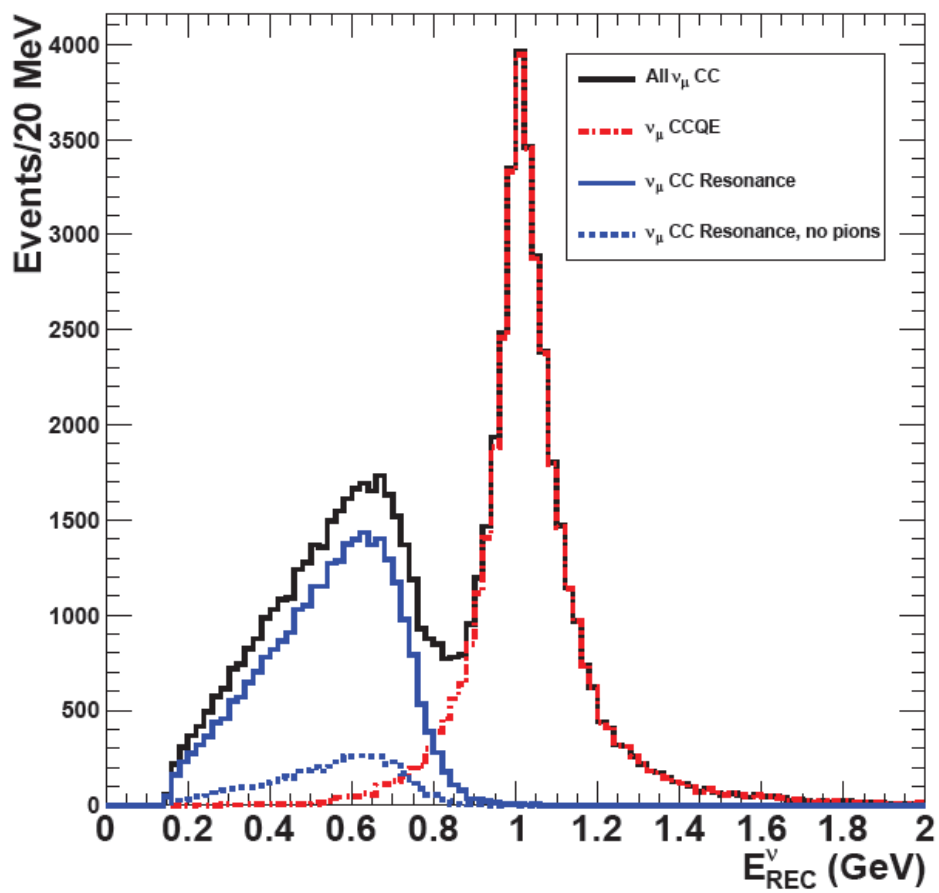
- (Kinematic) E_ν reconstruction via CCQE scattering:

$$\nu_l\, n \rightarrow l^-\, p$$
$$\nu_l\, p \rightarrow l^+\, n$$

$$E_\nu = \frac{2m_n E_\mu - m_\mu^2 - m_n^2 + m_p^2}{2(m_n - E_\mu + p_\mu \cos\theta_\mu)}$$

  - Not exact on nuclear targets
  - CCQE-like events from
    - absorbed pions
    - 2p2h
    - ...

GENIE E_ν = 1 GeV



Relevance for oscillation experiments

- (Calorimetric) E_ν reconstruction (e.g. MINOS)
  - $E_\nu = E_{lep} + E_{had}$

but

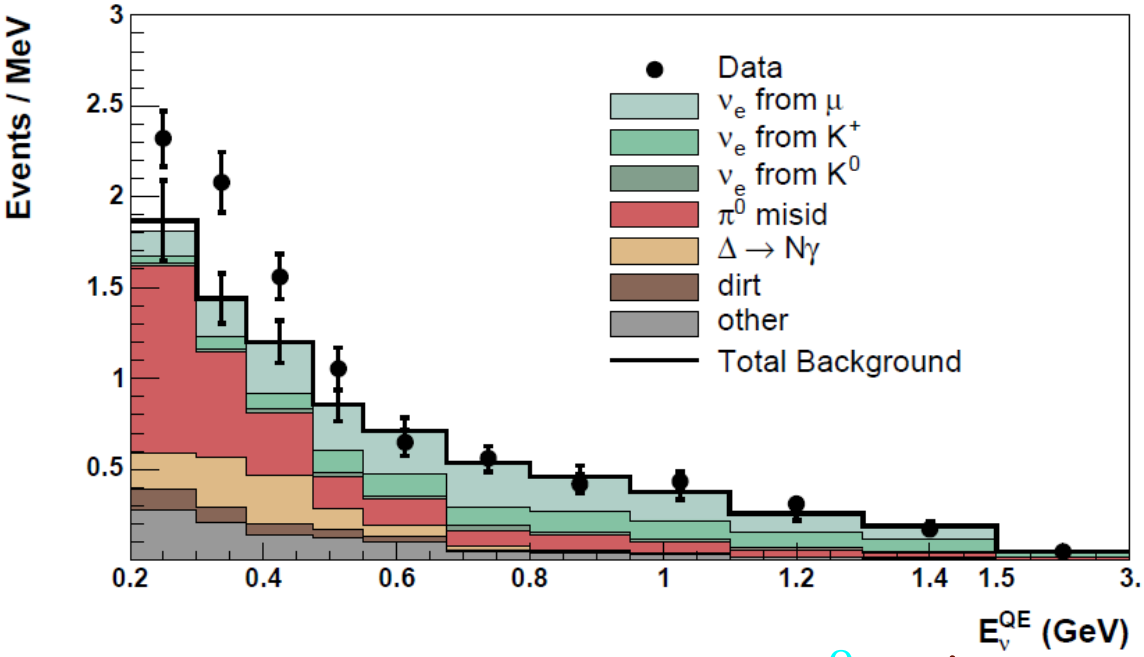
  - There are invisible heavy fragments, neutrons or other undetected particles: $E_{vis} < E_{had}$

  - E_{vis} -> E_{had} relies on the simulation

Relevance for oscillation experiments

- Backgrounds
  - E.g. in the MiniBooNE $\nu_\mu \to \nu_e$ search

Aguilar-Arevalo et al., PRL102 (2009) 101802



  - NC backgrounds: $\nu_l\, N \to \nu_l\, \pi^0\, N'$

$$\nu_l\, N \to \nu_l\, \gamma\, N'$$

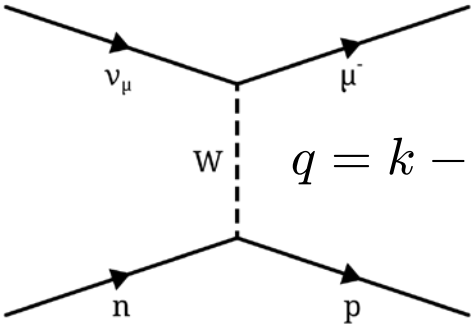
  - Also important for $\nu_\mu \to \nu_e$ measurements at T2K

Introduction

- Quasielastic(like) scattering
- Single pion production
- NC Single photon emission
- Strangeness production

ν QE scattering on the nucleon

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



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

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

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

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

- Vector form factors: $F_{12}^V = F_{12}^p - F_{12}^n$

$$G_E = F_1 + \frac{q^2}{2m_N}F_2 \quad \leftarrow \text{electric}$$

$$G_M = F_1 + F_2 \quad \leftarrow \text{magnetic}$$

ν QE scattering on the nucleon

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$$\bar{\nu}(k) + p(p) \rightarrow l^+(k') + n(p')$$
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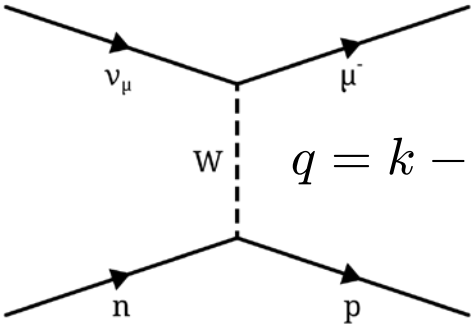

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- Axial form factors:

$$F_A(Q^2) = g_A F(Q^2)\,,\; F_P(Q^2) = \frac{2M^2}{Q^2 + m_\pi^2} F_A(Q^2)\,,\; Q^2 = -q^2 > 0$$

g_A = 1.267 $\leftarrow$ β decay

PCAC

QE scattering on the nucleon

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

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

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

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

  - The CCQE c.s. at low q2 depends on a small number of nucleon properties: charges, magnetic moments, mean squared radii

QE scattering on the nucleon

- 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)

  - From π electroproduction on p:

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

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

CCQE on nuclear targets

- Recent M_A "measurements":
  - K2K on H_2O : $M_A = 1.20 \pm 0.12$
  - MiniBooNE on CH_2 : $M_A = 1.35 \pm 0.17$ GeV
  - MINOS on Fe : $M_A = 1.26\ ^{+0.12}_{-0.10}\ ^{+0.08}_{-0.12}$ GeV

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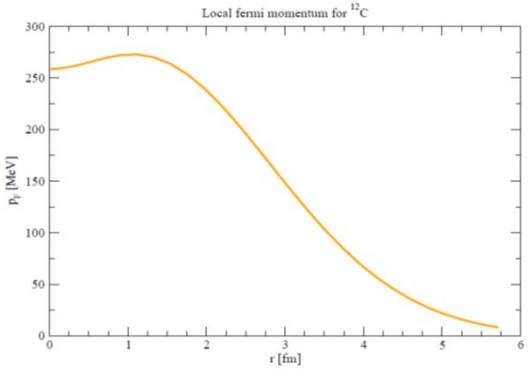
- Have these experiments really measured M_A ?
  - No, what has been measured is a parameter M_A^{eff}
    - Specific for the Relativistic Global Fermi Gas model
    - Target dependent
    - Flux dependent

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

CCQE on nuclear targets



- Improved nuclear effects
- Local Fermi Gas
  - $p_F(r) = [\frac{3}{2}\pi^2\rho(r)]^{1/3}$
  - Space-momentum correlations absent in the GFG
- Spectral functions

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

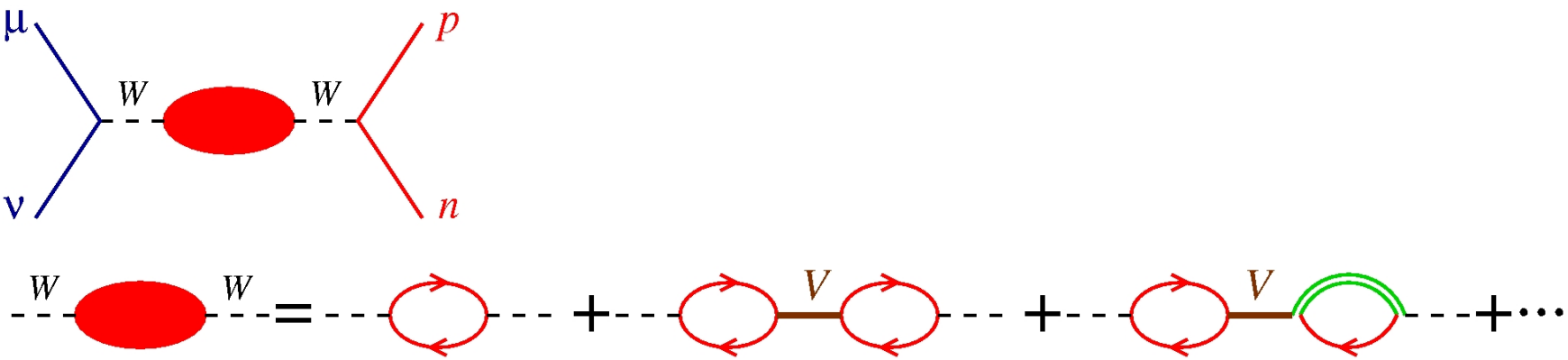
$$G(p) = \frac{1}{p^0 + E_p - i\epsilon}\left[\int_{-\infty}^{\mu}\frac{\mathcal{A}_h(\omega,\vec{p})}{p^0-\omega-i\epsilon}d\omega + \int_{\mu}^{\infty}\frac{\mathcal{A}_p(\omega,\vec{p})}{p^0-\omega+i\epsilon}d\omega\right]$$

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

- ImΣ = 0 $\Rightarrow$ mean-field approximation
- (Super)scaling

CCQE on nuclear targets

- Improved nuclear effects
- Long range RPA correlations
  - Beyond the Impulse Approximation

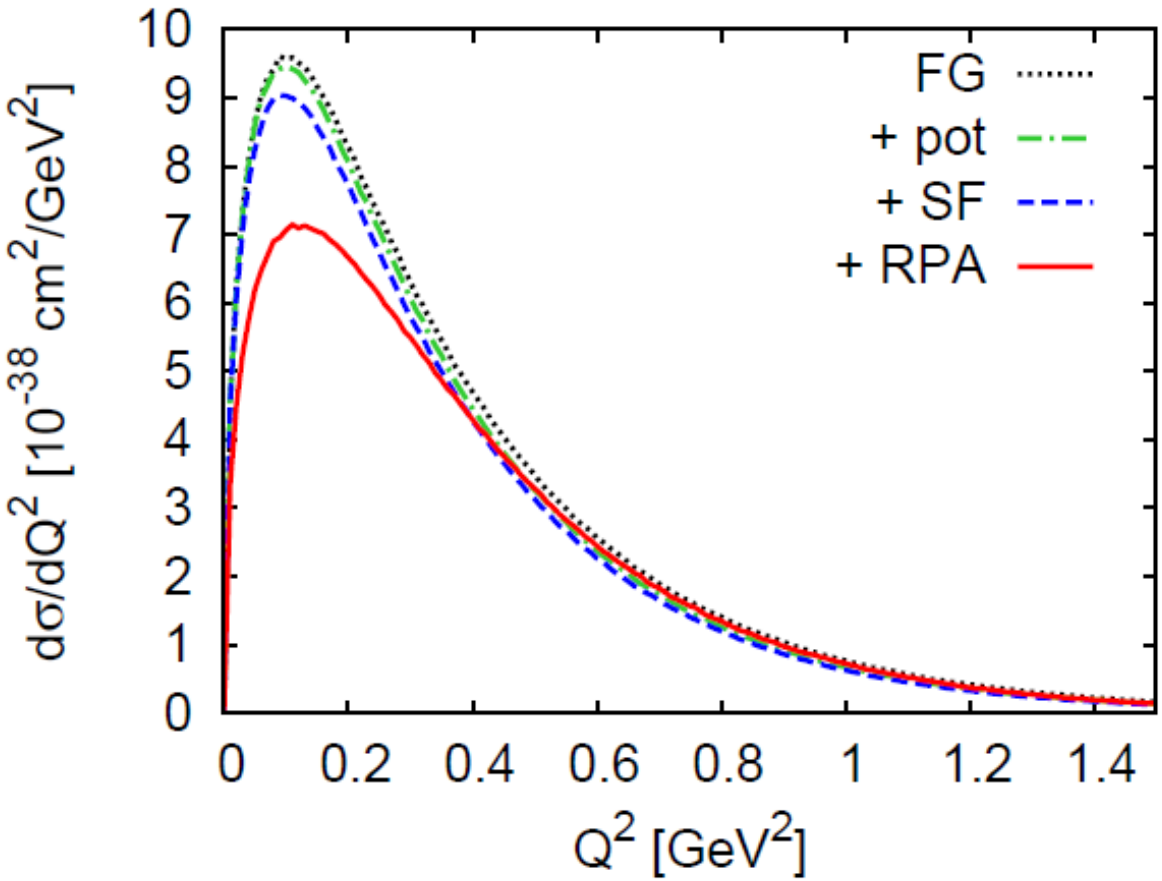


- RPA equation: $\Pi_{\mathrm{RPA}} = \Pi_0 + \Pi_0 V \Pi_{\mathrm{RPA}}$

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

CCQE on nuclear targets

- Improved nuclear effects
- Long range RPA correlations

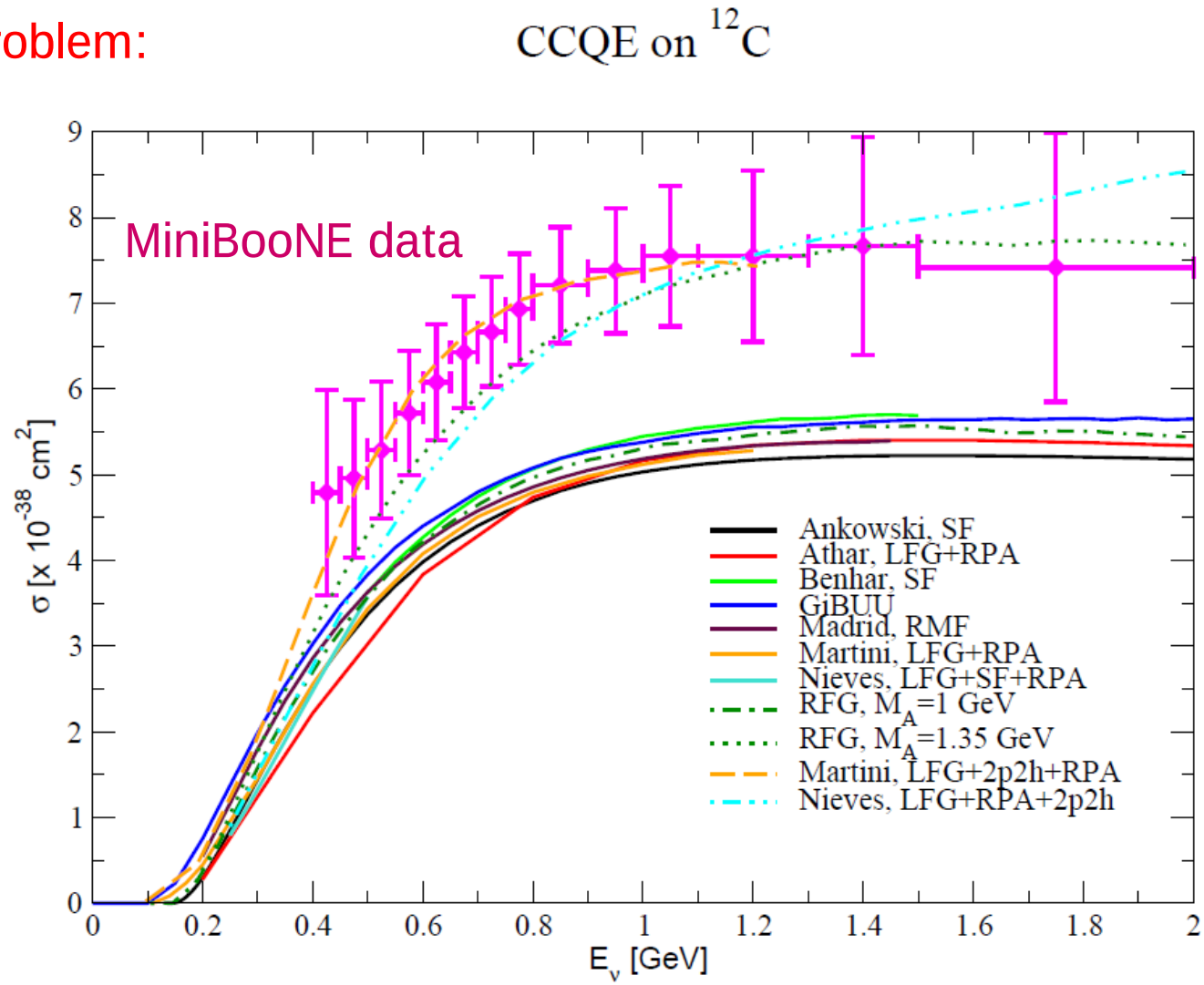


eraction

CCQE on ^{12}C averaged over the MiniBooNE flux

CCQE on nuclear targets

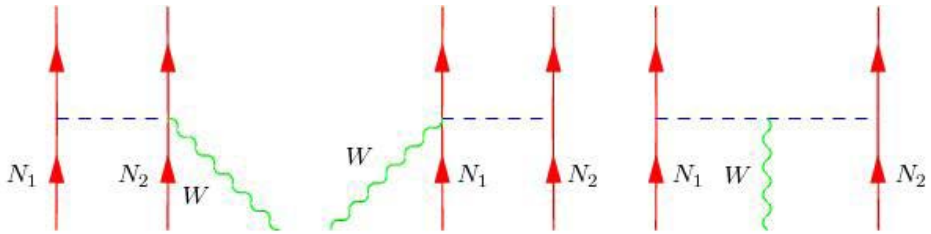
The problem:



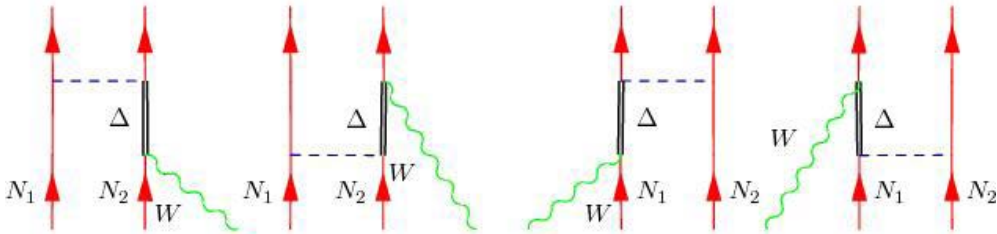
CCQE-like on nuclear targets

The solution:

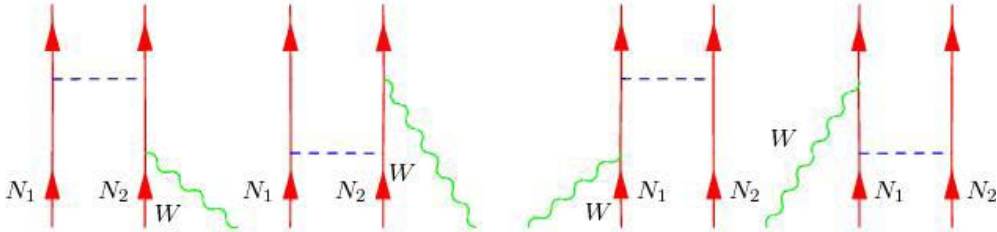
- multinucleon (2p2h) contributions
  - Martini et al., PRC 80 (2009)
  - Nieves et al., PRC 83 (2011)
  - Amaro et al., PLB 696 (2011)
- + RPA (important at low Q^2)



Contact and *pion-in-flight* diagrams



Δ-Meson Exchange Current diagrams



Correlation diagrams

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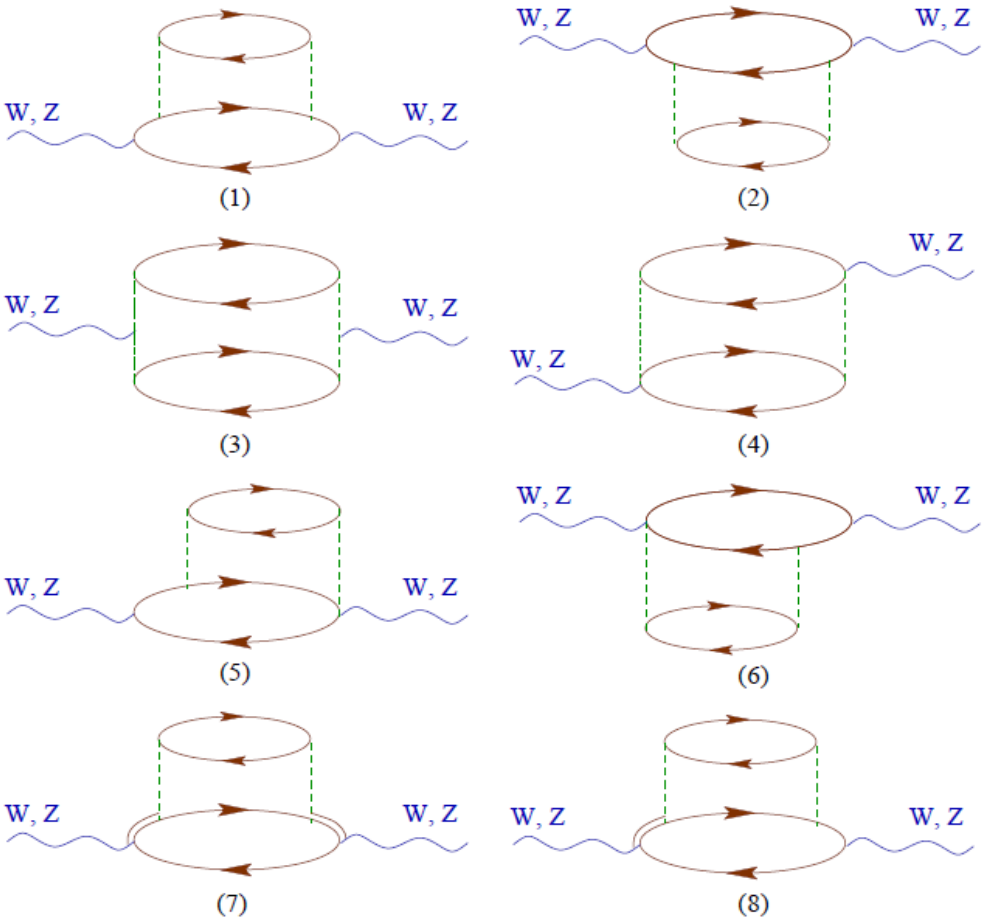
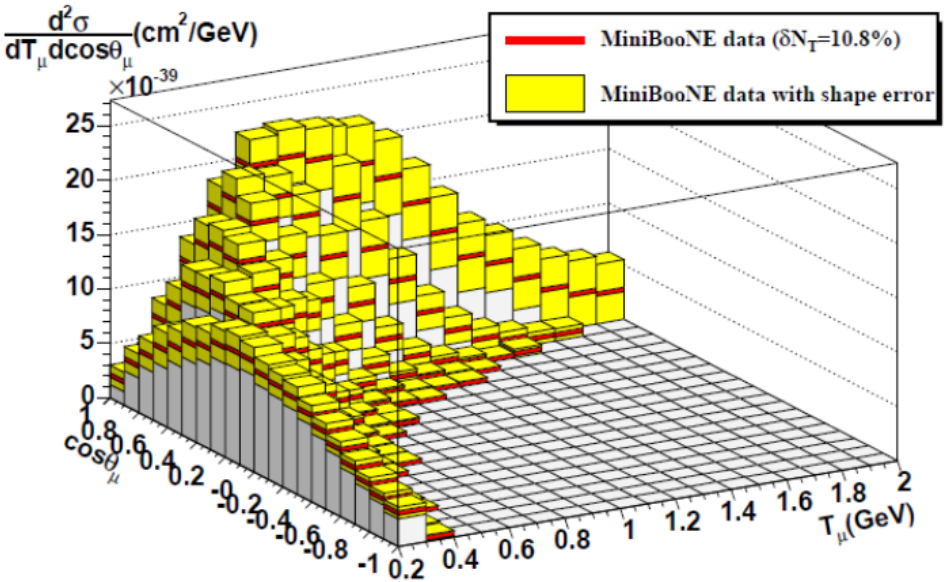
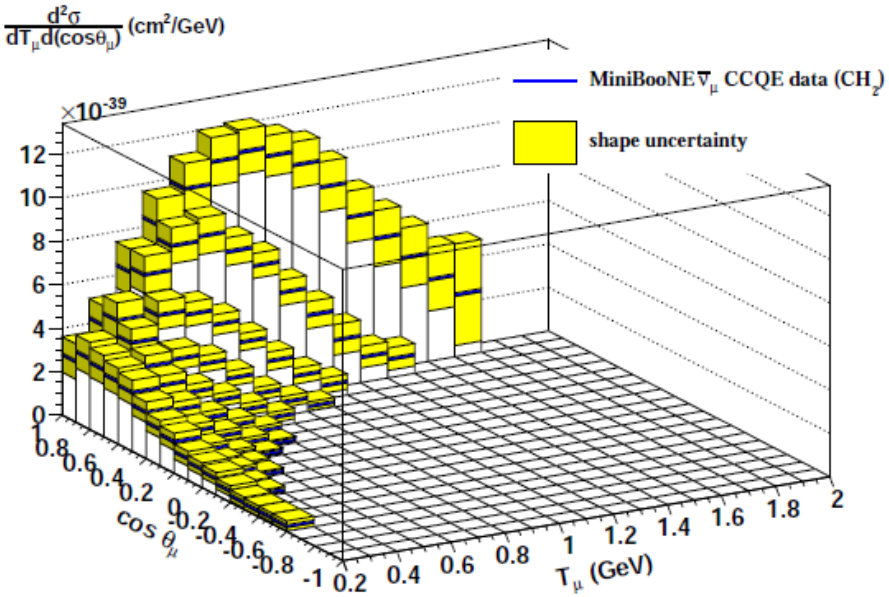


CCQE-like on nuclear targets

- 2-D CCQE-like cross section on CH_2 @ MiniBooNE





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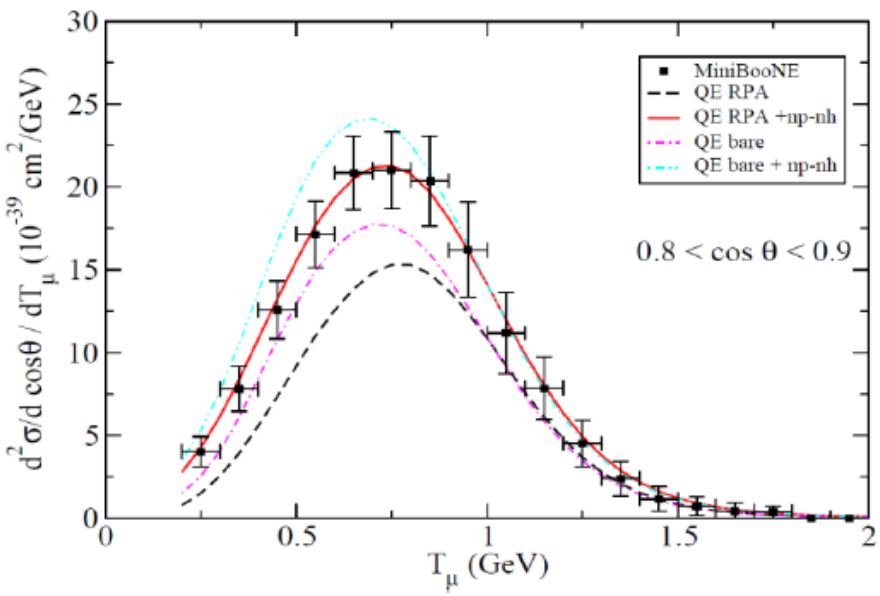
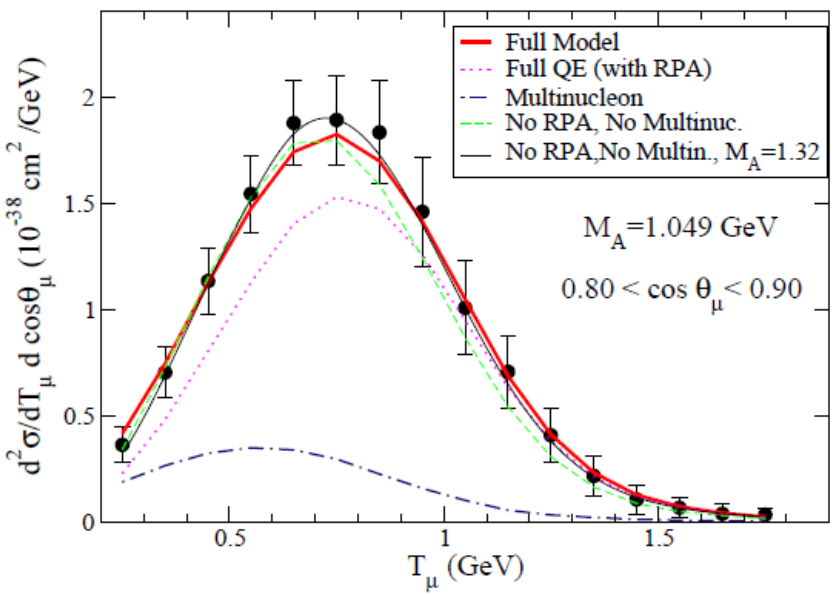
Martini et al.

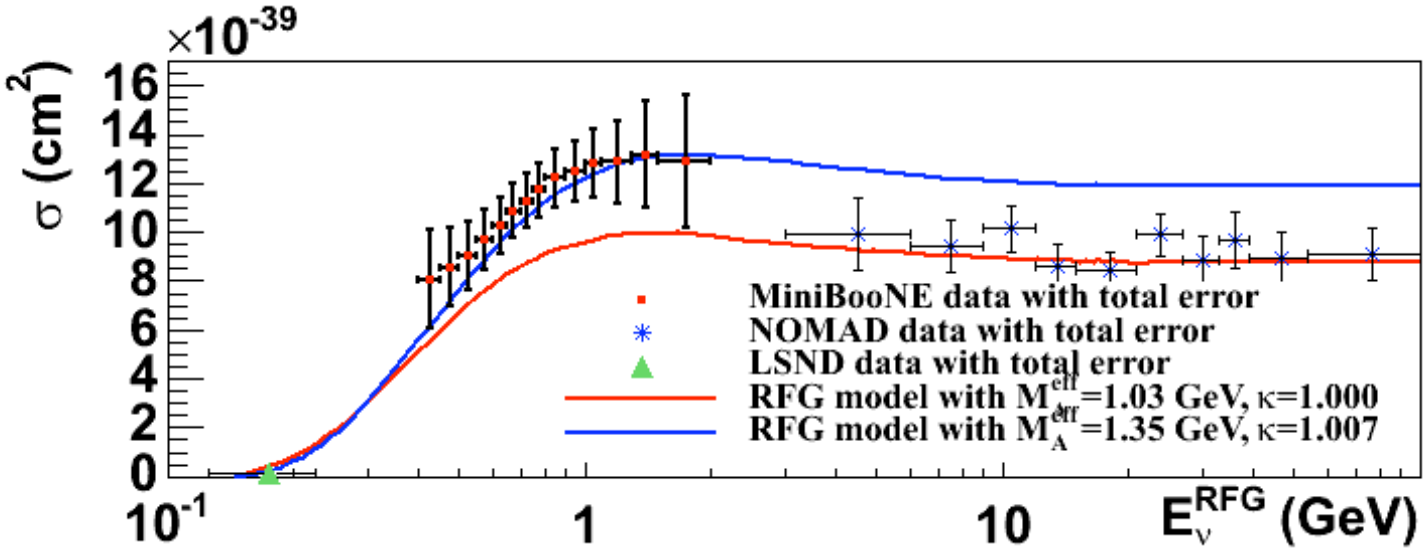


Nieves et al.



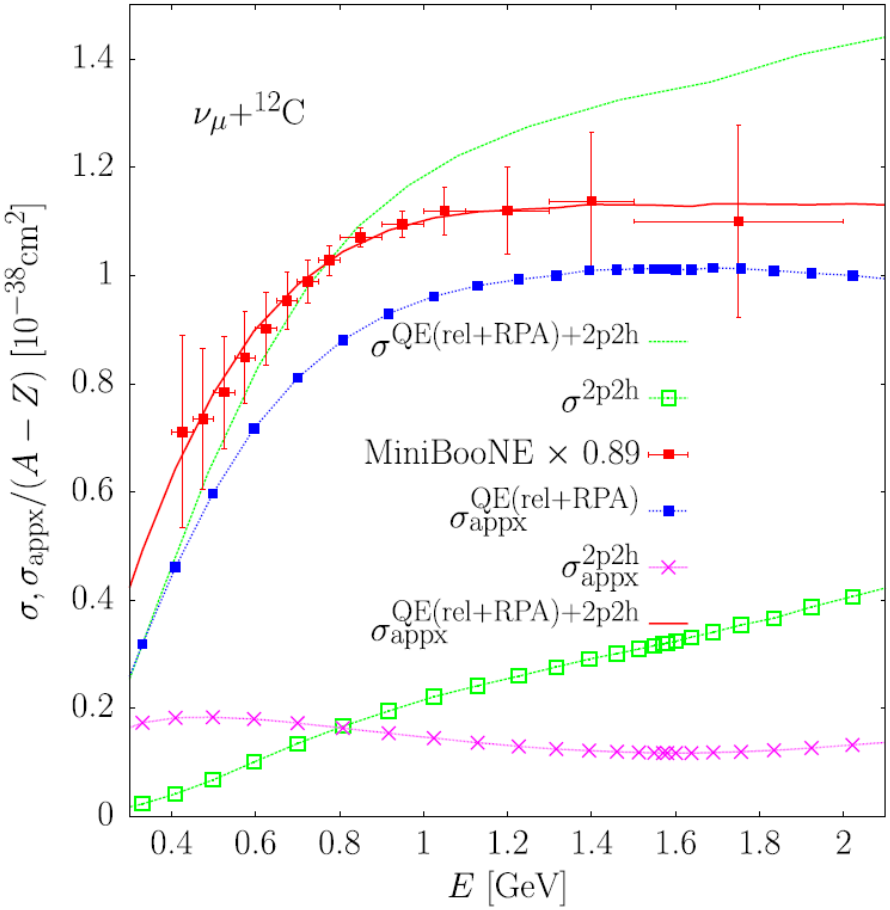
Experimental status

- NOMAD Lyubushkin et al., EPJ C 63 (2009) 355
- CCQE on ^{12}C at high 3-100 GeV energies (DIS is dominant)
- No precise knowledge of the integrated ν flux $\Rightarrow$
- Normalization of CCQE σ from processes with better know σ (DIS, IMD)
- CCQE σ measured from combined 2-track (μ,p) and 1-track (μ) samples
- From measured CCQE σ : M_A = 1.05 $\pm$ 0.02(stat) $\pm$ 0.06(sys) GeV



MiniBooNE vs NOMAD
Katori, arXiv:0909.1996

2p2h and E_ν energy reconstruction

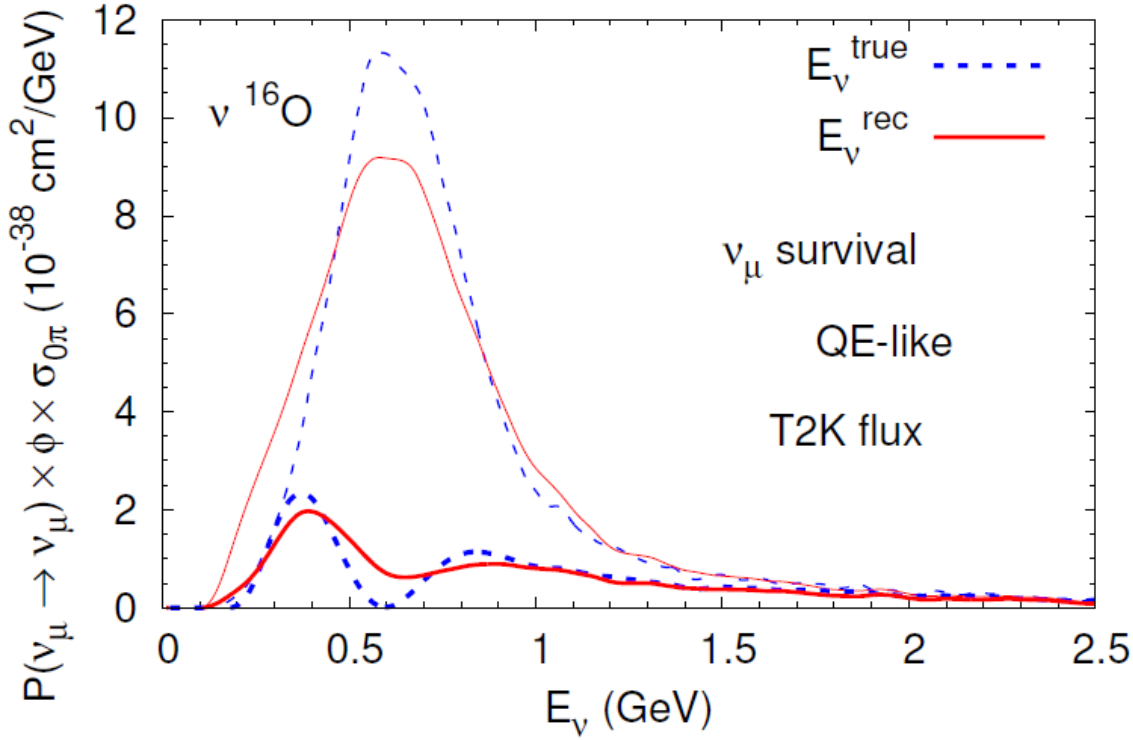


Nieves et al., PRD 85 (2012)

- E_ν misreconstruction is bound to have an impact in oscillation analyses

Lalakulich, Mosel, PRC 86 (2012); Coloma, Huber, PRL 111(2013)

2p2h and E_ν energy reconstruction



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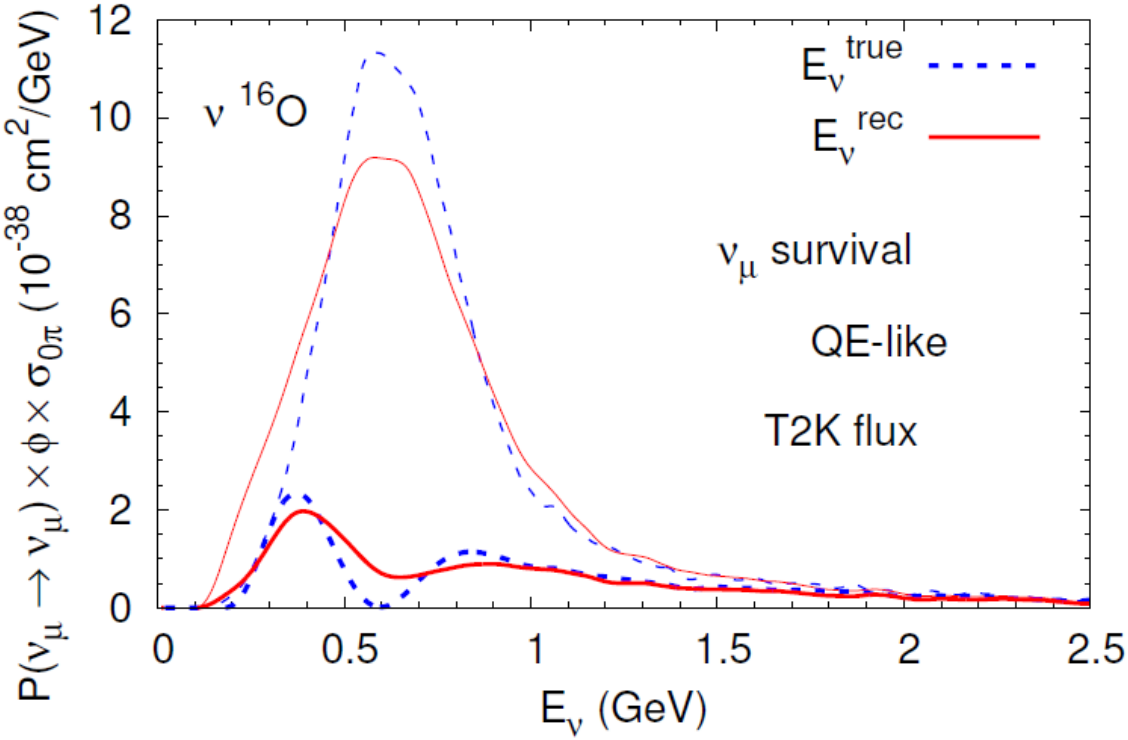


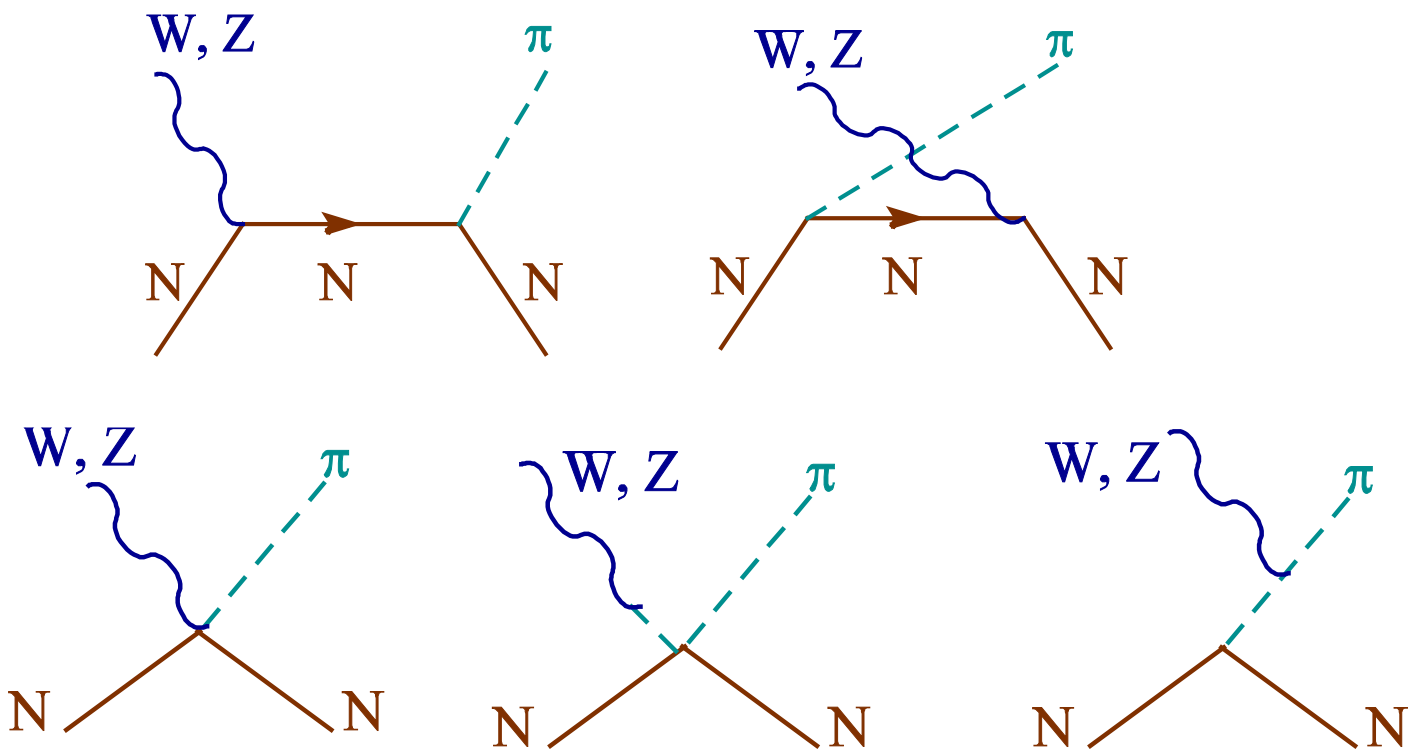
- E_ν misreconstruction is bound to have an impact oscillation analyses

  Lalakulich, Mosel, PRC 86 (2012); Coloma, Huber, PRL 111(2013)
- Bias remains after the ND is taken into account

1π production on the nucleon

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

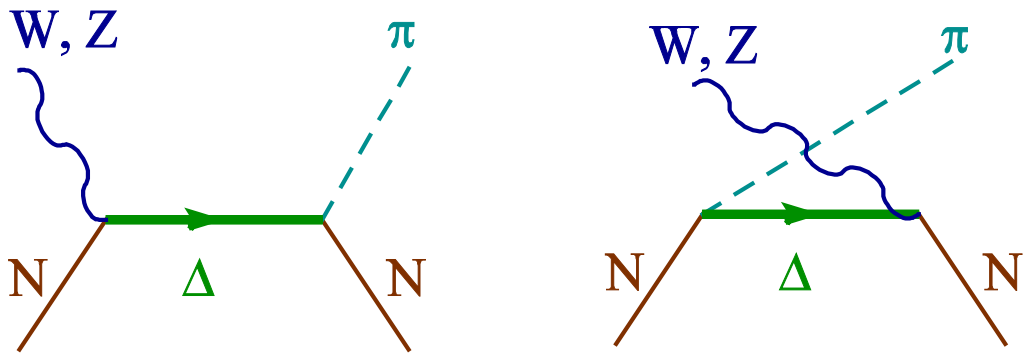
- From Chiral symmetry:



- but this in not enough

1π production on the nucleon

- Δ (1232) excitation:



- N-Δ transition current:

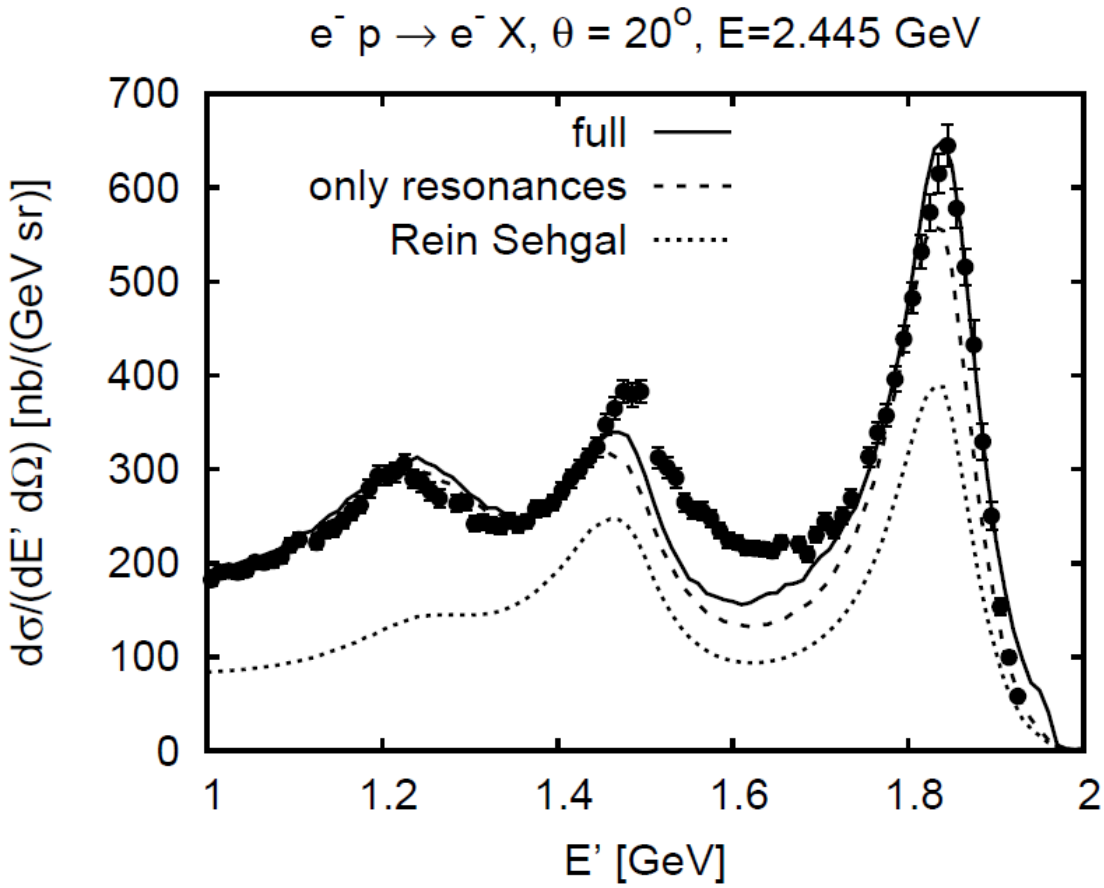
$$J^\mu = \bar{\psi}_\mu \left[\left(\frac{C_3^V}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{C_4^V}{M^2}(g^{\beta\mu} q\cdot p' - q^\beta p'^\mu) + \frac{C_5^V}{M^2}(g^{\beta\mu} q\cdot p - q^\beta p^\mu) \right)\gamma_5 \right.$$
$$\left. + \frac{C_3^A}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu)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

- Vector form factors $\Leftrightarrow$ Helicity amplitudes

1π production on the nucleon

- Resonance excitation in ν MC generators:

- Rein-Sehgal model: Rein-Sehgal, Ann. Phys. 133 (1981) 79.
- Helicity amplitudes for 18 baryon resonances
- Poor description of π electroproduction data on p

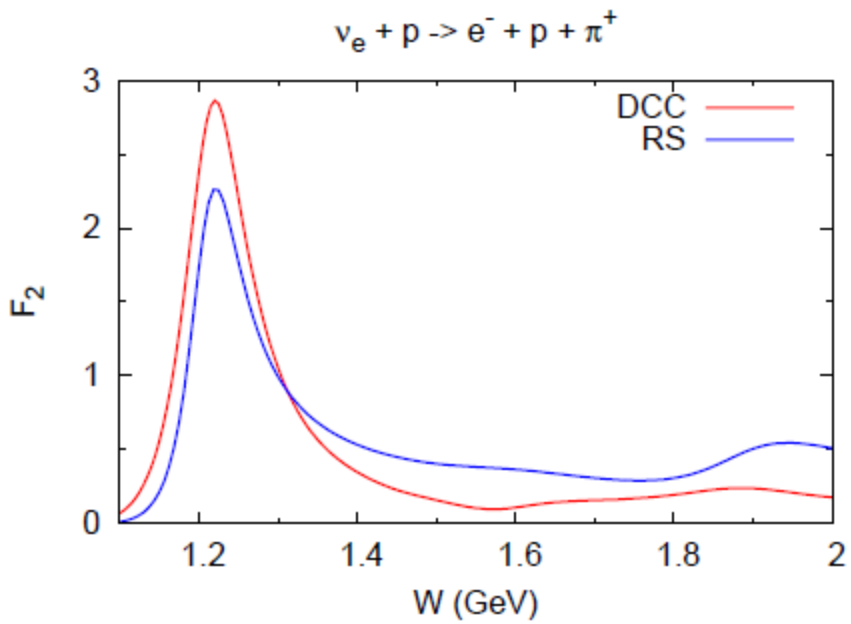


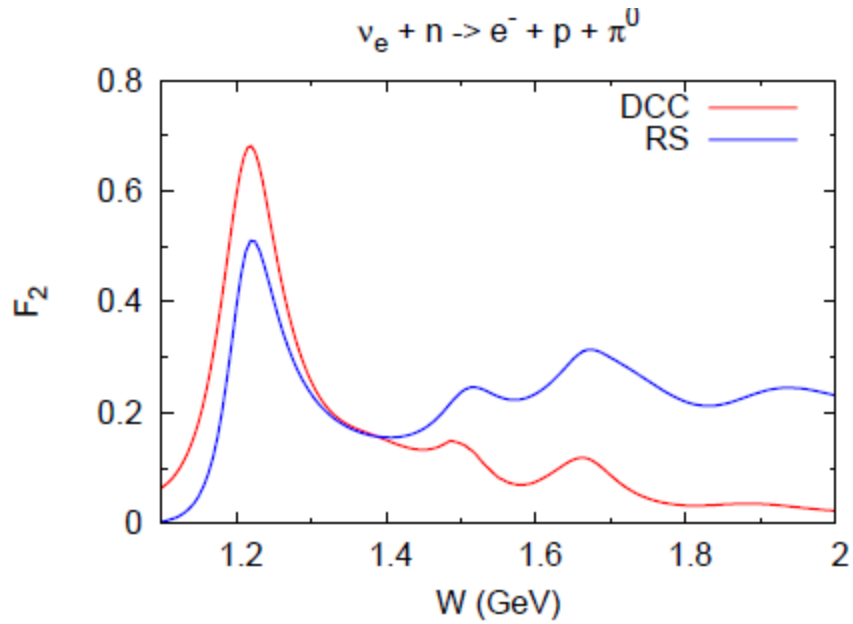
1π production on the nucleon

- Resonance excitation in ν MC generators:

- Rein-Sehgal model: Rein-Sehgal, Ann. Phys. 133 (1981) 79.
- Helicity amplitudes for 18 baryon resonances
- Poor in the axial sector (at $q^2 = 0$). PCAC :

$$F_2(W, q^2 = 0) \propto \sigma_{\pi N \to X}(\sqrt{s} = W)$$





- DCC = Dynamical coupled channel model

Kamano et al., PRD 86 (2012)

1π production on the nucleon

- N-Δ transition current

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

- Helicity amplitudes can be extracted from data on π photo- and electro-production

$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^+ J_{\mathrm{EM}}^\mu \right| N, J_z = -1/2 \right\rangle \zeta$$

$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 3/2 \left| \epsilon_\mu^+ J_{\mathrm{EM}}^\mu \right| N, J_z = 1/2 \right\rangle \zeta$$

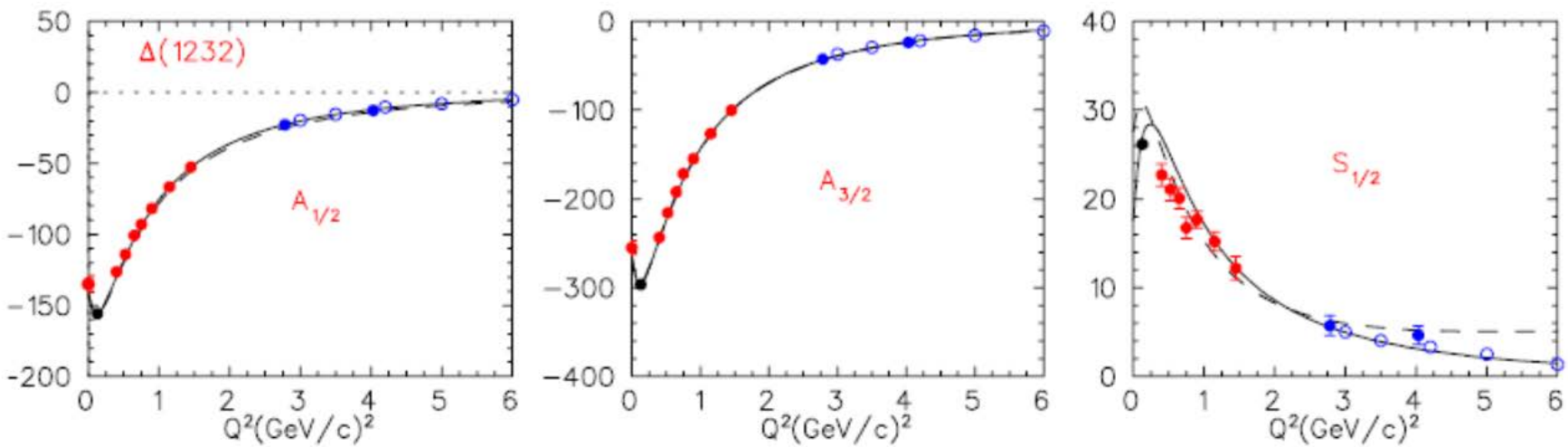
$$S_{1/2} = -\sqrt{\frac{2\pi\alpha}{k_R}} \frac{|\mathbf{q}|}{\sqrt{Q^2}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^0 J_{\mathrm{EM}}^\mu \right| N, J_z = 1/2 \right\rangle \zeta$$

1π production on the nucleon

- 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 Tiator et al., EPJ Special Topics 198 (2011)



1π production on the nucleon

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  - Axial form factors

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

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

  - Constraints from ANL and BNL data on $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$
    - with large normalization (flux) uncertainties
  - ANL and BNL data do not constrain $C^A_{3,4}$

1π production on the nucleon

- N-Δ axial form factors: determination of $C^A_5(0)$ and $M_{A\,\Delta}$
- $C_5^A = C_5^A(0)\left(1+\frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$
- From ANL and BNL data on $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$
- Hernandez et al., PRD 81 (2010)
  - Deuteron effects
  - $C^A_5(0)$ =1.00 $\pm$ 0.11, $M_{A\,\Delta}$ = 0.93 $\pm$ 0.07 GeV
  - 20% reduction of the GT relation $C_5^A(0) = \frac{g_{\Delta N\pi} f_\pi}{\sqrt{6}M} \approx 1.2 \leftarrow$ off diagonal GT relation
- LAR, Hernandez, Nieves (2014), preliminary
  - Unitarization in the leading vector and axial multipoles
  - Phases enforced to correspond to π N $\to$ π N (Watson's theorem)
  - $C^A_5(0)$ =1.12 $\pm$ 0.11, $M_{A\,\Delta}$ = 0.95 $\pm$ 0.06 GeV

Weak Resonance excitation

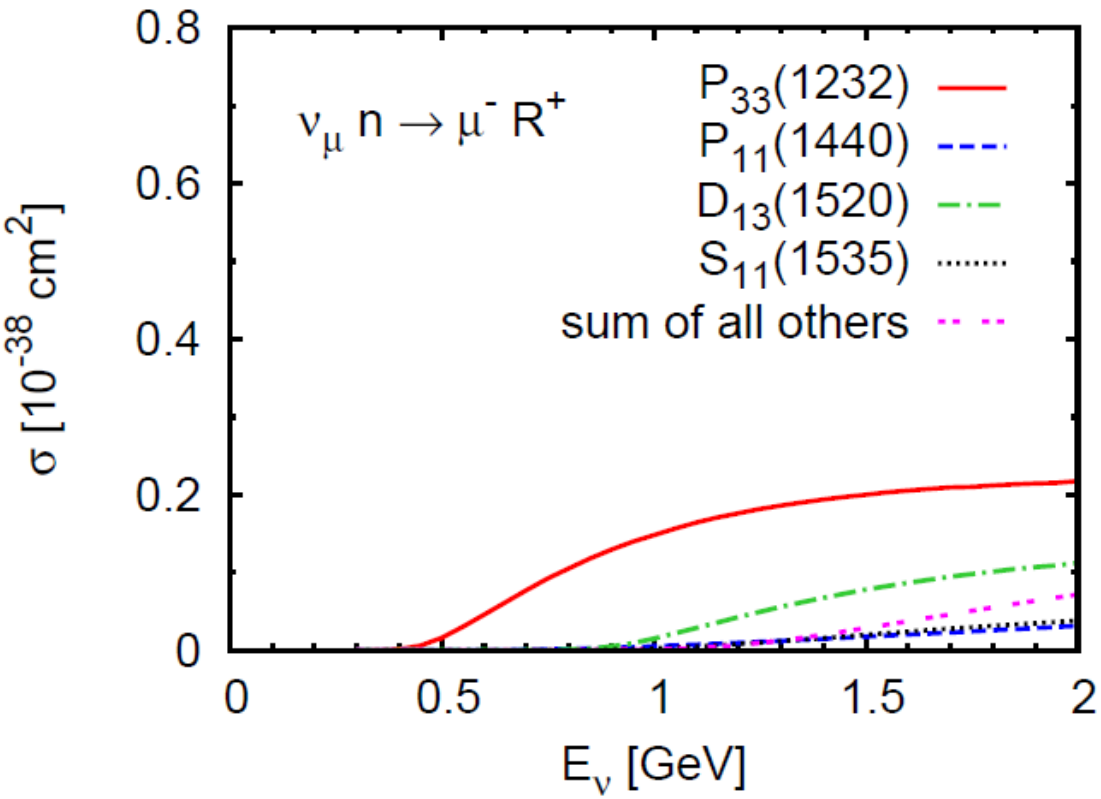
- Baryon resonances contribute to:
  - the inclusive $\nu_l\, N \to l\, X$ cross section
  - several exclusive channels: $\nu_l\, N \to l\, N'\, \pi$

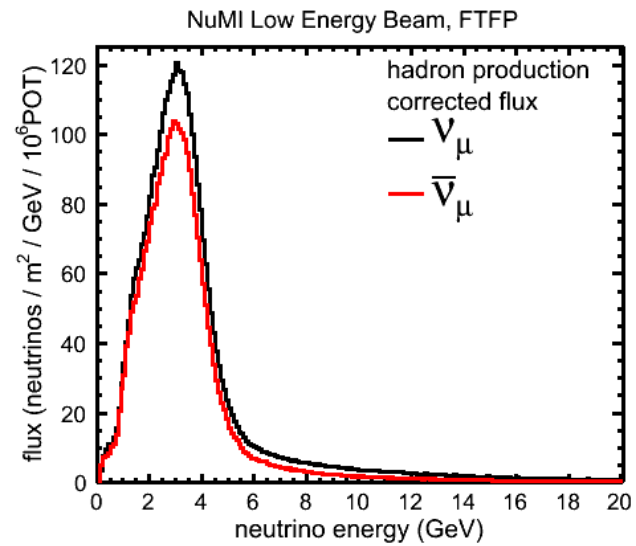
    $\nu_l\, N \to l\, N'\, \gamma$

    $\nu_l\, N \to l\, N'\, \eta$

    $\nu_l\, N \to l\, \Lambda(\Sigma)\, \bar{K}$
  - At $E_\nu \sim 1$ GeV (MiniBooNE, SciBooNE, T2K,...) $\Delta(1232)$ is dominant
  - At E_ν>1 GeV (MINERνA) N* become also important

Inclusive resonance production



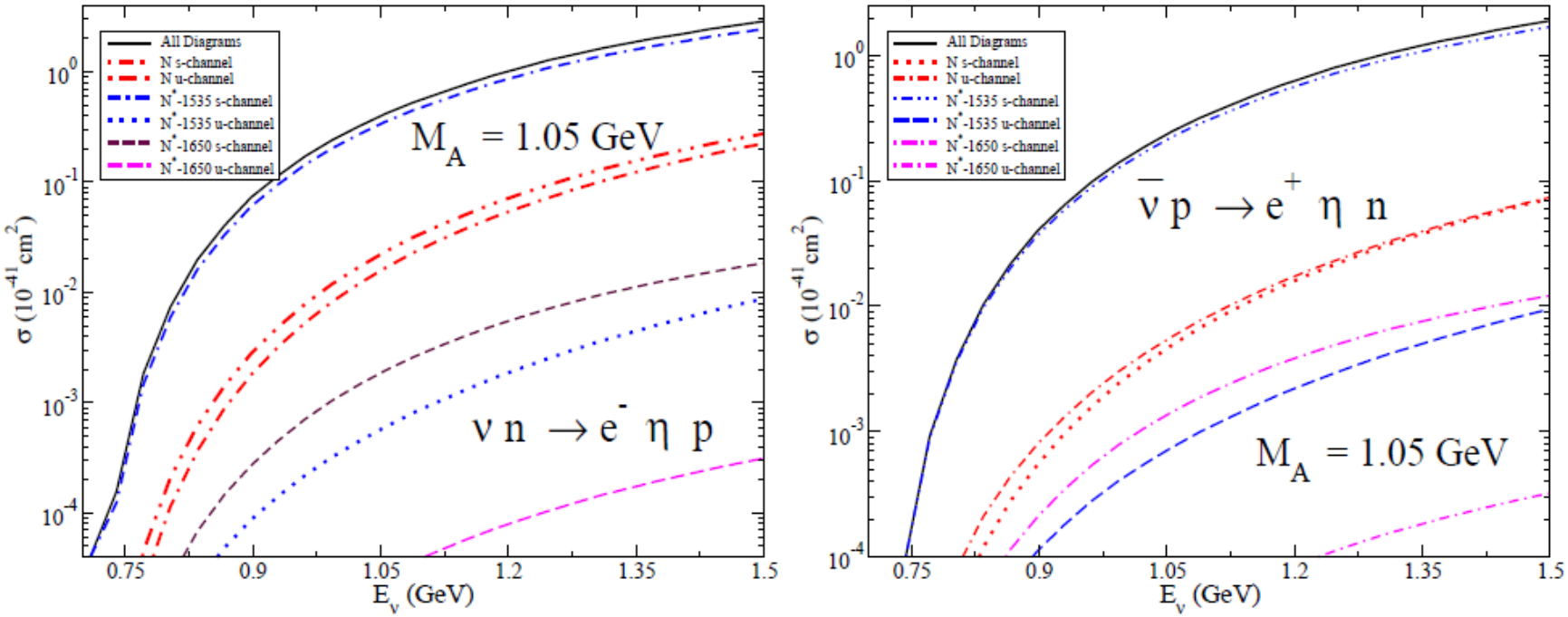


T. Leitner, O. Buss, LAR, U. Mosel, PRC 79 (2009)
T. Leitner, PhD Thesis, 2009

- At E_ν = 2 GeV, CCN*(1520)/CCΔ $\sim$ 0.5, CCN*(1440,1535)/CCΔ $\sim$ 0.22
- N*(1520) is important for $\nu_l\, N \rightarrow l\, N'\, \pi$

Weak η production

- LAR, M. Sajjad Athar, M. Rafi Alam, M. J. Vicente Vacas
- $\nu_l \, N \to l \, N' \, \eta$
- Ingredients: s,u-channel nucleon pole, N*(1535), N*(1650)
- (Preliminary) Results:



- The N*(1535) excitation is dominant
- Small cross section but large enought to be measured at MINERνA

1π production on nuclei

- Incoherent 1π production in nuclei

$$\nu_l \, A \rightarrow l \, \pi \, X$$

  - Modification of the $\Delta(1232)$ properties in the medium

$$D_\Delta \Rightarrow \tilde{D}_\Delta(r) = \frac{1}{(W + M_\Delta)(W - M_\Delta - \mathrm{Re}\Sigma_\Delta(\rho) + i\tilde{\Gamma}_\Delta/2 - i\mathrm{Im}\Sigma_\Delta(\rho))}$$

$\tilde{\Gamma}_\Delta \leftarrow$ Free width $\Delta \rightarrow$ N π modified by Pauli blocking

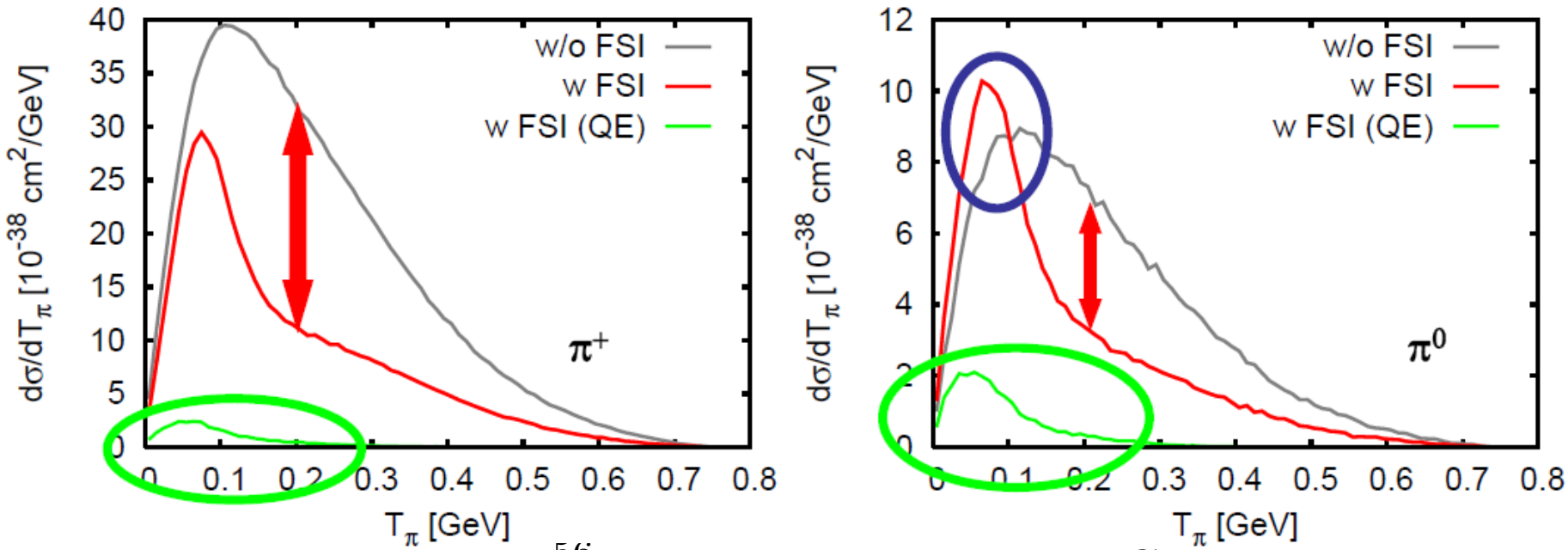
$$\mathrm{Re}\Sigma_\Delta(\rho) \approx 40\mathrm{MeV}\frac{\rho}{\rho_0}$$

$\mathrm{Im}\Sigma_\Delta(\rho) \leftarrow$
- Δ N $\rightarrow$ N N
- Δ N $\rightarrow$ N N π
- Δ N N $\rightarrow$ N N N

  - π propagation (scattering, charge exchange), absorption (FSI)
    - semiclassical cascade, transport models

1π production on nuclei

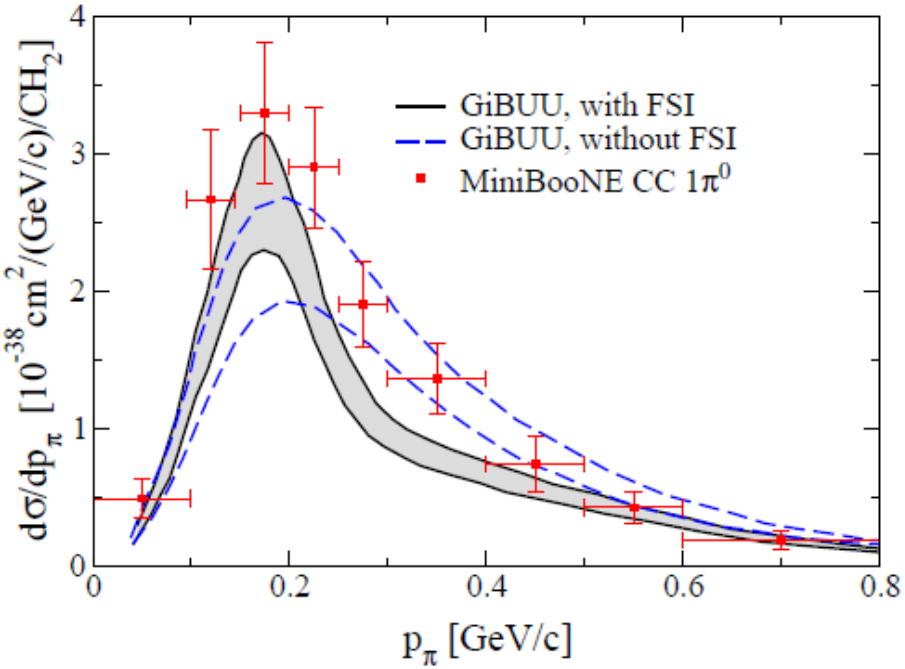
- GiBUU Leitner, LAR, Mosel, PRC 73 (2006)
  - Effects of FSI on pion kinetic energy spectra
    - strong absorption in Δ region
    - side-feeding from dominant π^+ into π^o channel
    - secondary pions through FSI of initial QE protons

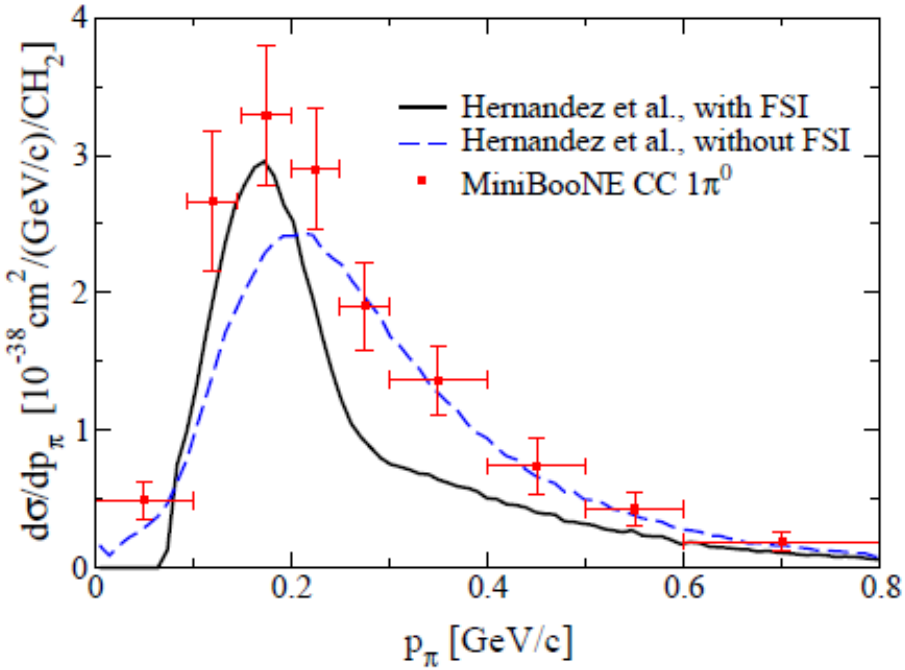


$$\nu_\mu + {}^{56}Fe \to \mu^- \pi X \quad E_\nu = 1 \text{ GeV}$$

1π production on nuclei

- Comparison to MiniBooNE





- Two-nucleon mechanisms (?)

Weak coherent reactions

- Coherent = final nucleus remains in the ground state
  - Neutral Current elastic scattering

$$\nu\, A \to \nu\, A$$

$$\bar{\nu}\, A \to \bar{\nu}\, A$$

  - Charged Current coherent particle production

$$\nu_l\, A \to l^-\, m^+\, A$$

$$\bar{\nu}_l\, A \to l^+\, m^-\, A$$

$$m^\pm = \pi^\pm\,, K^\pm\,, \rho^\pm\,, \ldots$$

  - Neutral Current coherent particle production

$$\nu\, A \to \nu\, m^0\, A$$

$$\bar{\nu}\, A \to \bar{\nu}\, m^0\, A$$

$$m^0 = \gamma\,, \pi^0\,, \rho^0\,, \ldots$$

Weak coherent reactions

- Coherent = final nucleus remains in the ground state
  - Neutral Current elastic scattering

$$\nu\, A \to \nu\, A$$

$$\bar{\nu}\, A \to \bar{\nu}\, A$$

$$t = (p' - p)^2 = 2M_A^2 - 2M_A\sqrt{M_A^2 + \vec{p}'^2} \approx -2M_A T_A = q^2$$

$$\frac{d\sigma}{dT_A} = \frac{G_F^2}{4\pi}\left[F_n(Q^2) - (1 - 4\sin^2\theta_W)F_p^2(Q^2)\right]^2 M_A\left(1 - \frac{M_A T_A}{2E_\nu^2}\right)$$

  - Experimental problem: small recoil energies
  - Similar detection techniques than in **dark matter** experiments
  - (Potential) irreducible background in direct **dark matter** searches

Weak coherent reactions

- Coherent = final nucleus remains in the ground state
  - Neutral Current elastic scattering

$$\nu\, A \to \nu\, A$$

$$\bar{\nu}\, A \to \bar{\nu}\, A$$

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  - Neutral Current coherent particle production

$$\nu\, A \to \nu\, m^0\, A$$

$$\bar{\nu}\, A \to \bar{\nu}\, m^0\, A$$

$$m^0 = \gamma\,, \pi^0\,, \rho^0\,, \ldots$$

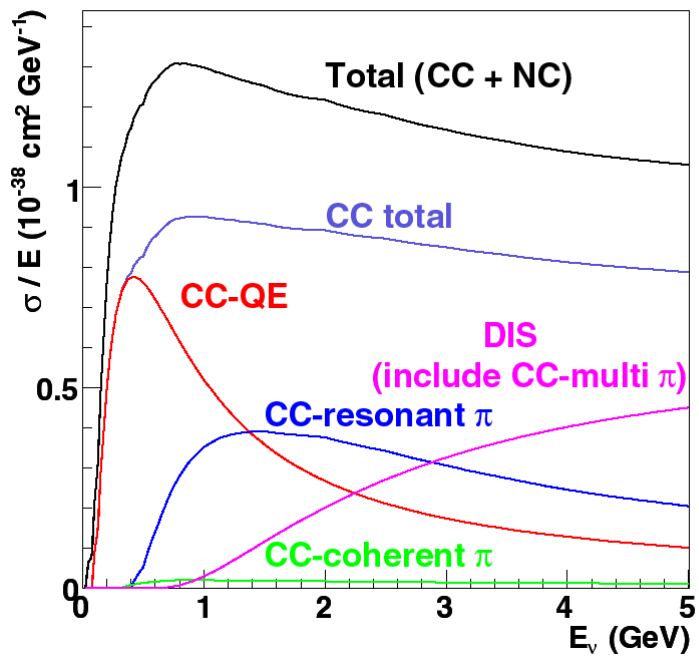
Coherent pion production

- m = π

$$\nu\, A \rightarrow \nu\, \pi^0\, A$$

$$\bar{\nu}\, A \rightarrow \bar{\nu}\, \pi^0\, A$$

- Very small cross section but relatively larger than in coherent π production with photons or electrons
- At $q^2 \sim 0$ the axial current is not suppressed while the vector is
- Background to QE when π^0 ($\pi^{\pm}$) is mistaken for a $e^{\pm}$ (p)



NEUT
Hiraide@NuInt09

PCAC models

- Rein-Sehgal NPB 223 (83) 29
  - In the $q^2=0$ limit, PCAC is used to relate ν induced coherent pion production to πA elastic scattering

$$\left.\frac{d\sigma}{dq^2 dy dt}\right|_{q^2=0} = \frac{G_F^2 f_\pi^2}{2\pi^2}\frac{(1-y)}{y}\frac{d\sigma}{dt}(\pi^0 A \to \pi^0 A)\Big|_{q^2=0,\, E_\pi=q^0}$$

$y=q^0/E_\nu$

  - Continuation to $q^2 \neq 0$: $\times\left(1-q^2/1\mathrm{GeV}^2\right)^{-2}$
  - πA in terms of πN scattering:

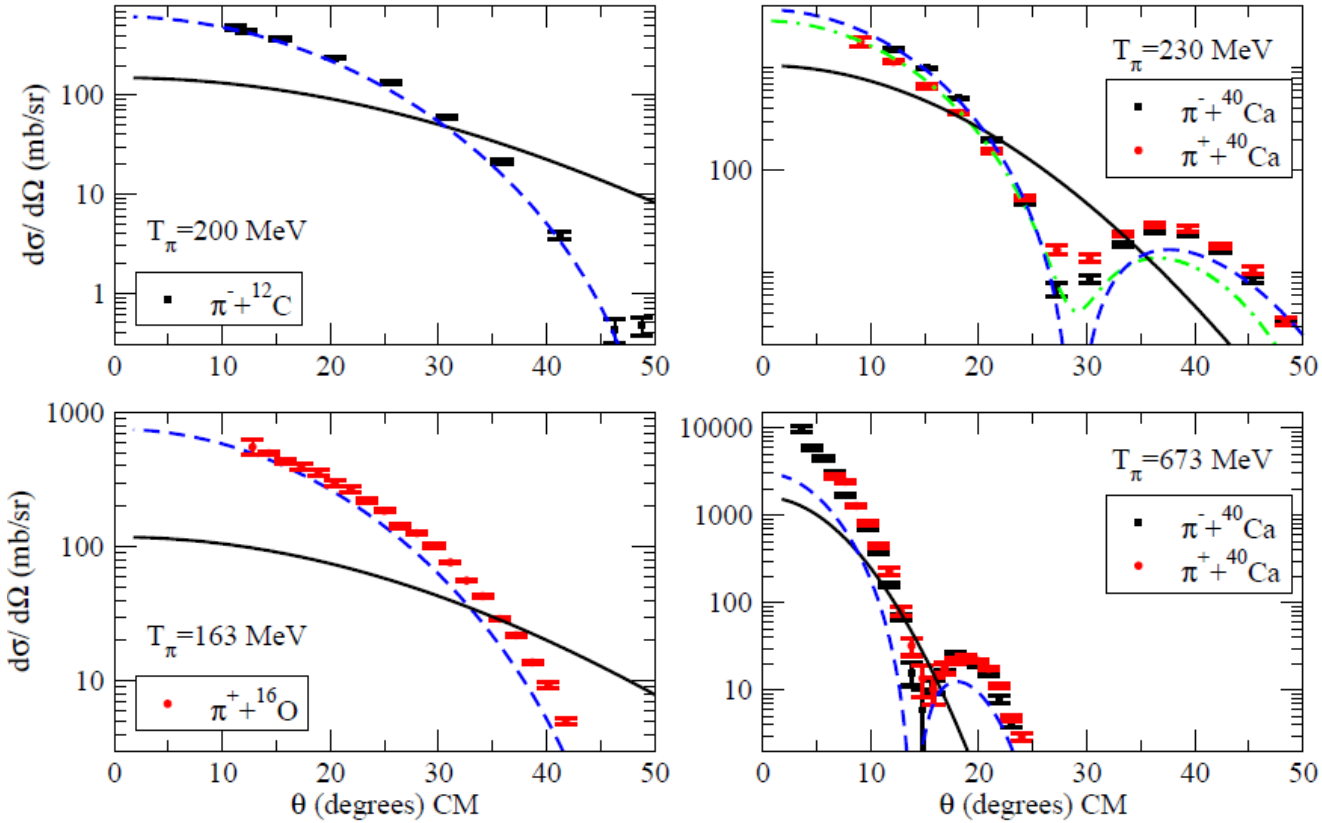
$$\times|F_{\mathcal{A}}(t)|^2\, F_{\mathrm{abs}}\left(\frac{d\sigma}{dt}(\pi^0 N \to \pi^0 N)\right)_{t=0,\, E_\pi=q^0}$$

$$F_{\mathcal{A}}(t) = \int d^3\vec{r}\, e^{\mathrm{i}(\vec{q}-\vec{p}_\pi)\cdot\vec{r}}\left\{\rho_p(\vec{r})+\rho_n(\vec{r})\right\}$$ ← nuclear form factor

F_{abs} ← removes from the flux outgoing π that undergo inelastic collisions

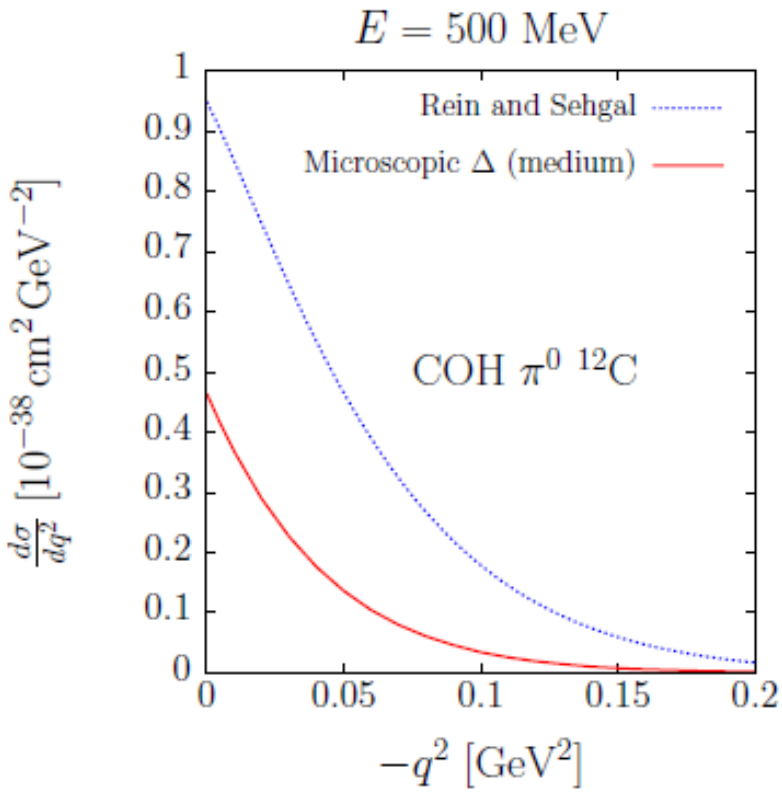
PCAC models

- Rein-Sehgal NPB 223 (83) 29
  - Problems: Hernandez et al., PRD 80 (2009) 013003
    - $q^2=0$ approximation neglects important angular dependence at low energies and for light nuclei
    - The πA elastic description is not realistic



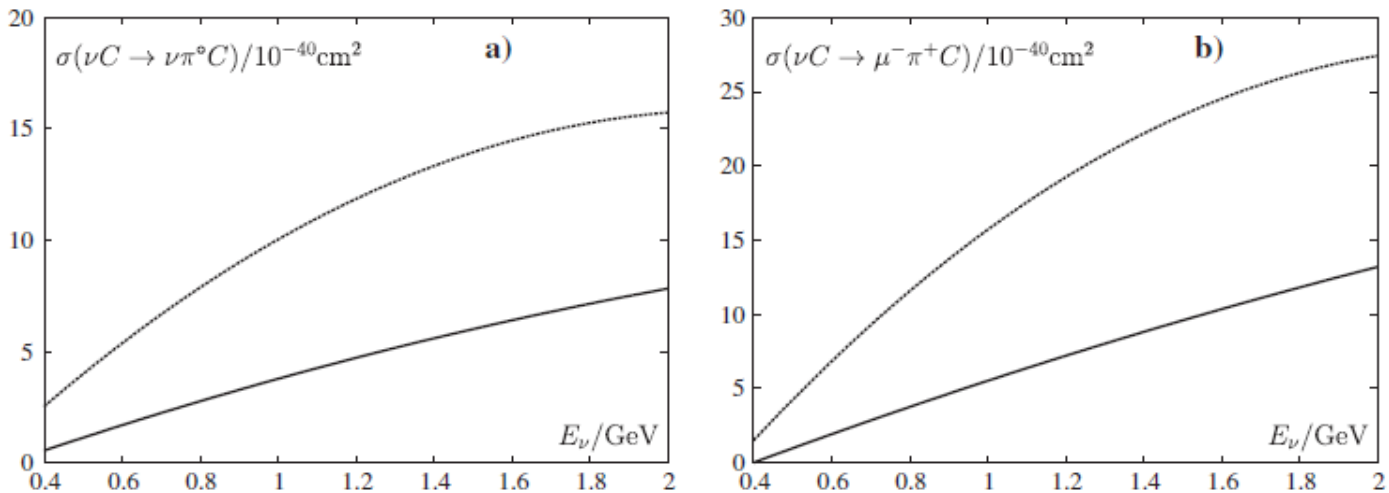
PCAC models

- Rein-Sehgal NPB 223 (83) 29
  - Problems: Hernandez et al., PRD 80 (2009) 013003
    - Predicts larger cross sections and wider q^2 distributions than microscopic models



PCAC models

- Kartavtsev et al., PRD 74 (2006), Berger & Sehgal, PRD 79 (2009), Paschos & Schalla, PRD 80 (2009)
  - Some $q^2 \neq 0$ kinematical corrections introduced
  - Use experimental πA cross section
  - Smaller σ than R&S:



R & S

B & S

PCAC models

- Problems of PCAC models: less relevant at high energies and heavy nuclei
  - NOMAD: σ=72.6 $\pm$ 8.1(stat) $\pm$ 6.9(syst) $\times$ 10^{-40} cm^2
  - Energy range: 2.5 $\leq$ E_ν $\leq$ 300 GeV
  - Consistent with R&S: $\sigma \approx 78 \times 10^{-40}$ cm^2

    Kullenberg et al., PLB 682 (2009) 177

Microscopic models

- Kelkar et al., PRC55 (1997); Singh et al., PRL 96 (2006); LAR et al., PRC 75, 76 (2007); Amaro et al., PRD 79 (2009), Nakamura et al, PRC 81 (2010); Zhang et al. PRC 86 (2012)
  - Model for the elementary $\nu\ N \rightarrow l\ N\ \pi$ amplitude
  - Coherent sum over all nucleons
  - Δ much more dominant than on nucleons, $\sigma \sim \left[C_5^A(0)\right]^2$
  - Δ properties changed in nuclei
  - Distortion of the outgoing pion $e^{-i\vec{p}_\pi \cdot \vec{r}} \rightarrow \phi^*_{out}(\vec{p}_\pi, \vec{r})$

$$\left(-\vec{\nabla}^2 - \vec{p}_\pi^2 + 2\omega_\pi \hat{V}_{\rm opt}\right)\phi^*_{out} = 0$$

$\hat{V}_{\rm opt}(r) \leftarrow$ Nonlocal optical potential in the Δ-hole model

- 👍 Same hadronic/nuclear input as for the incoherent(resonant) channel
- 👍 Can be applied/validated in other reactions (γ, e, π, ...)
- 👎 Limited to the Δ region and below
- 👎 Technically more complex and harder to implement than PCAC models

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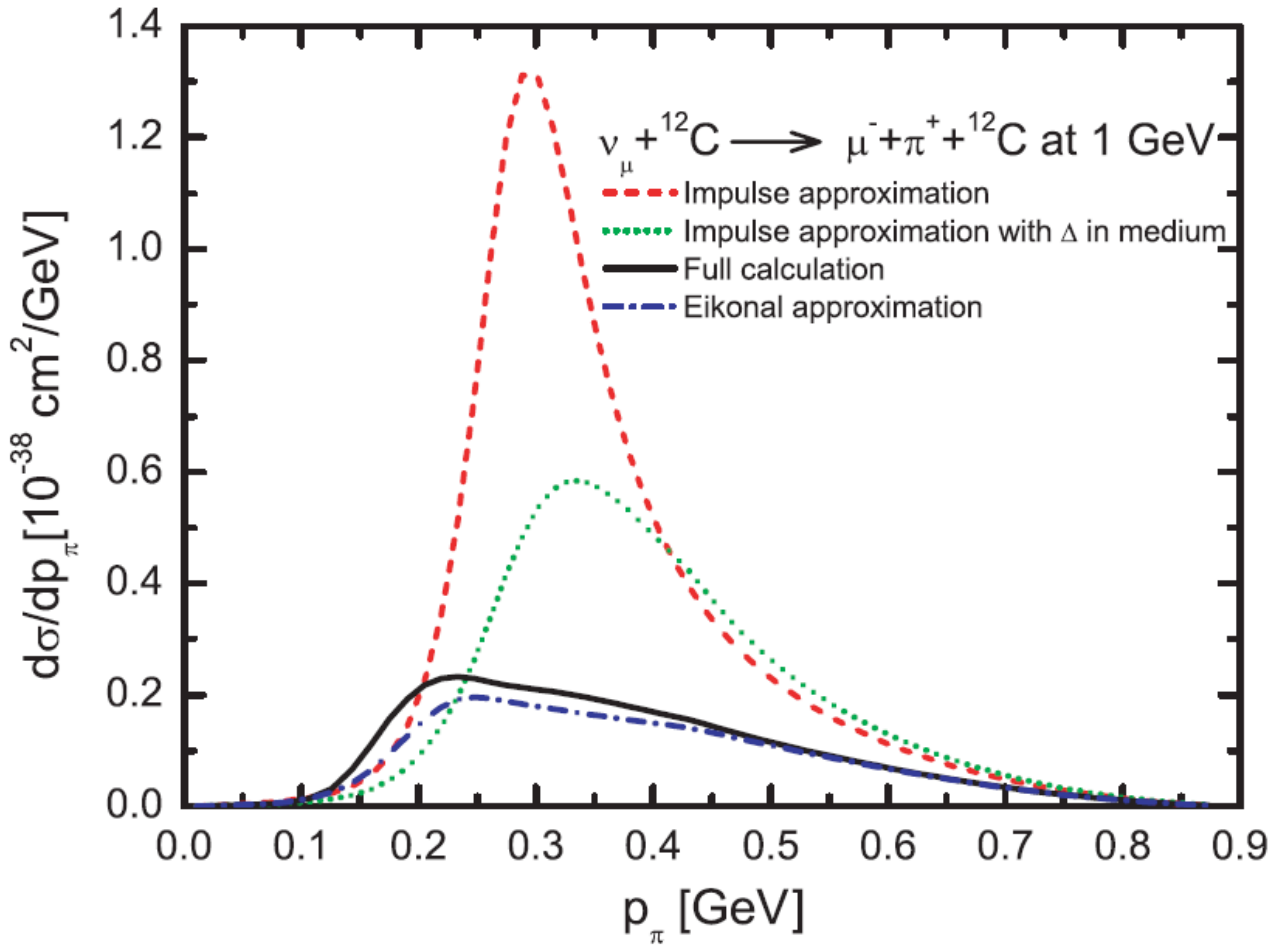

τ, $\vec{r}$)

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...)

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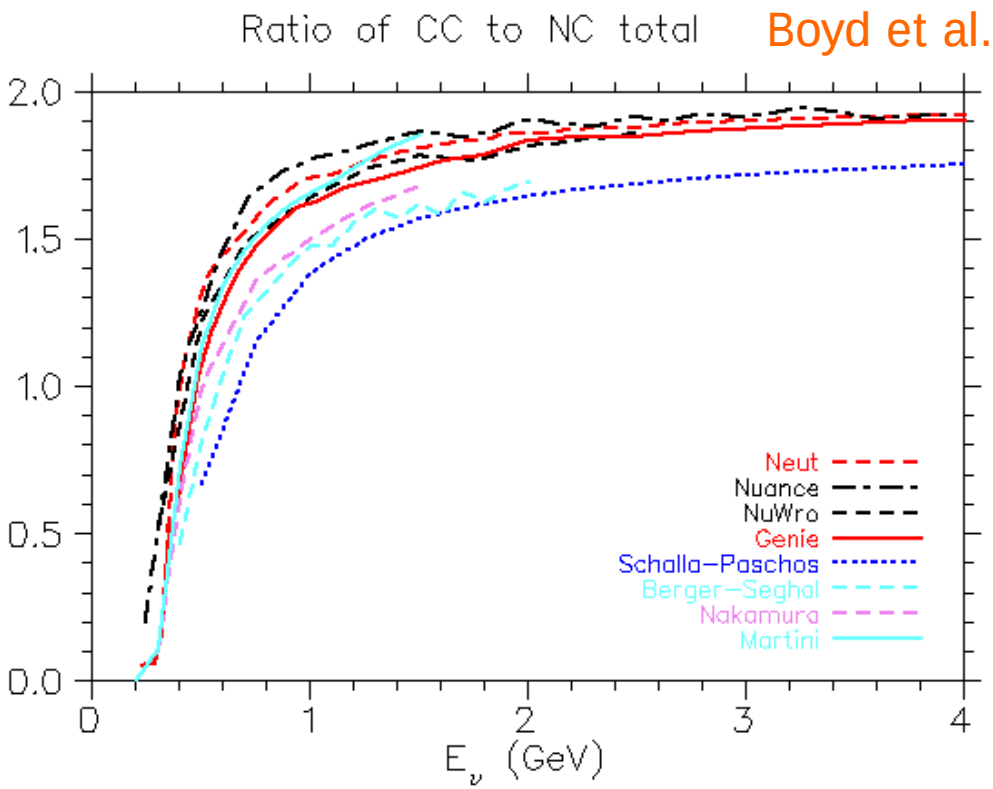
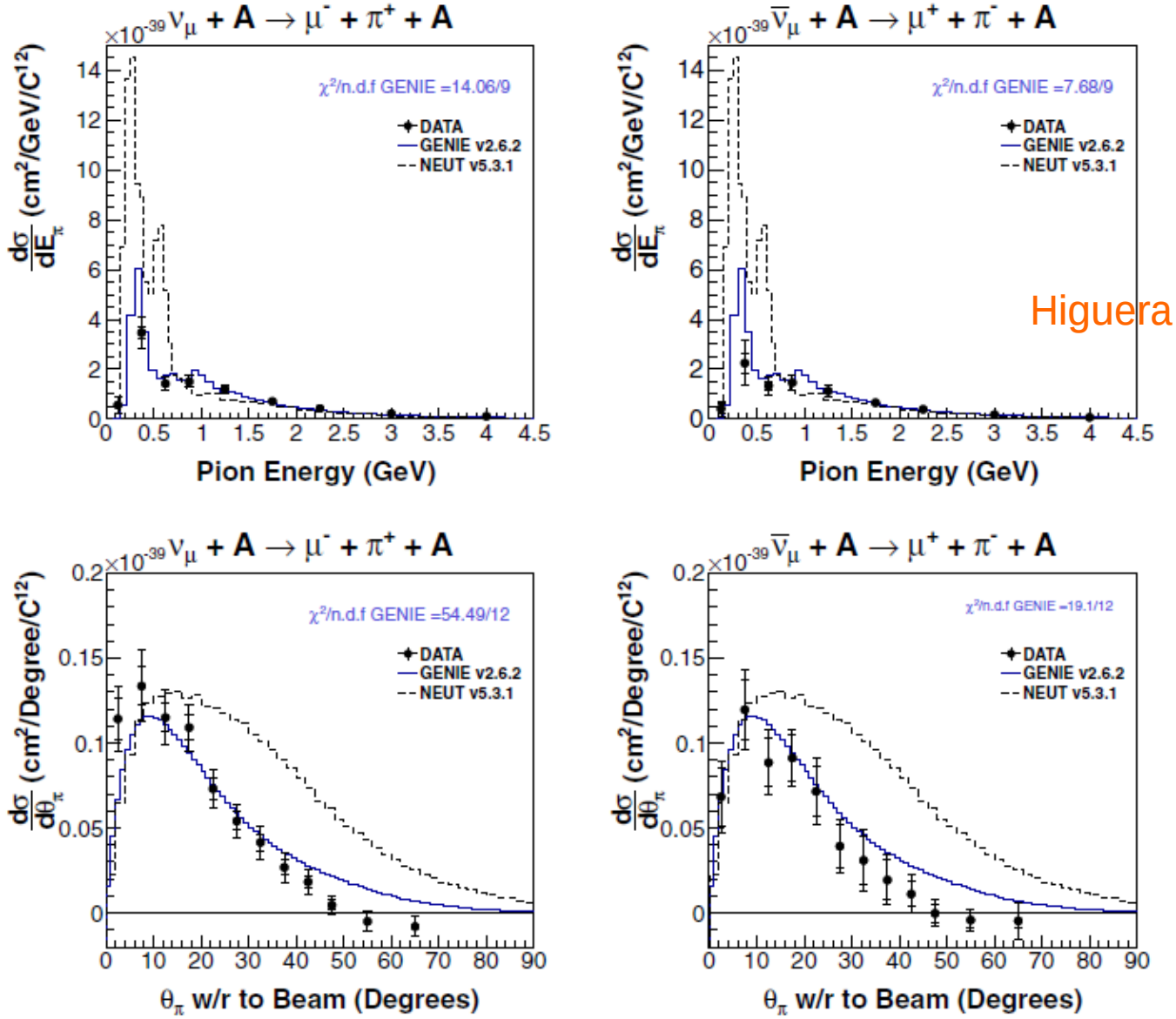
CC/NC ratio



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 !

MINERνA measurement



Higuera et al., PRL 113 (2014)

NCγ

- Photon emission in NC interactions:
  - on nucleons $\nu(\bar{\nu})\, N \rightarrow \nu(\bar{\nu})\, \gamma\, N$
  - on nuclei $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, X$ $\leftarrow$ incoherent

    $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, A$ $\leftarrow$ coherent

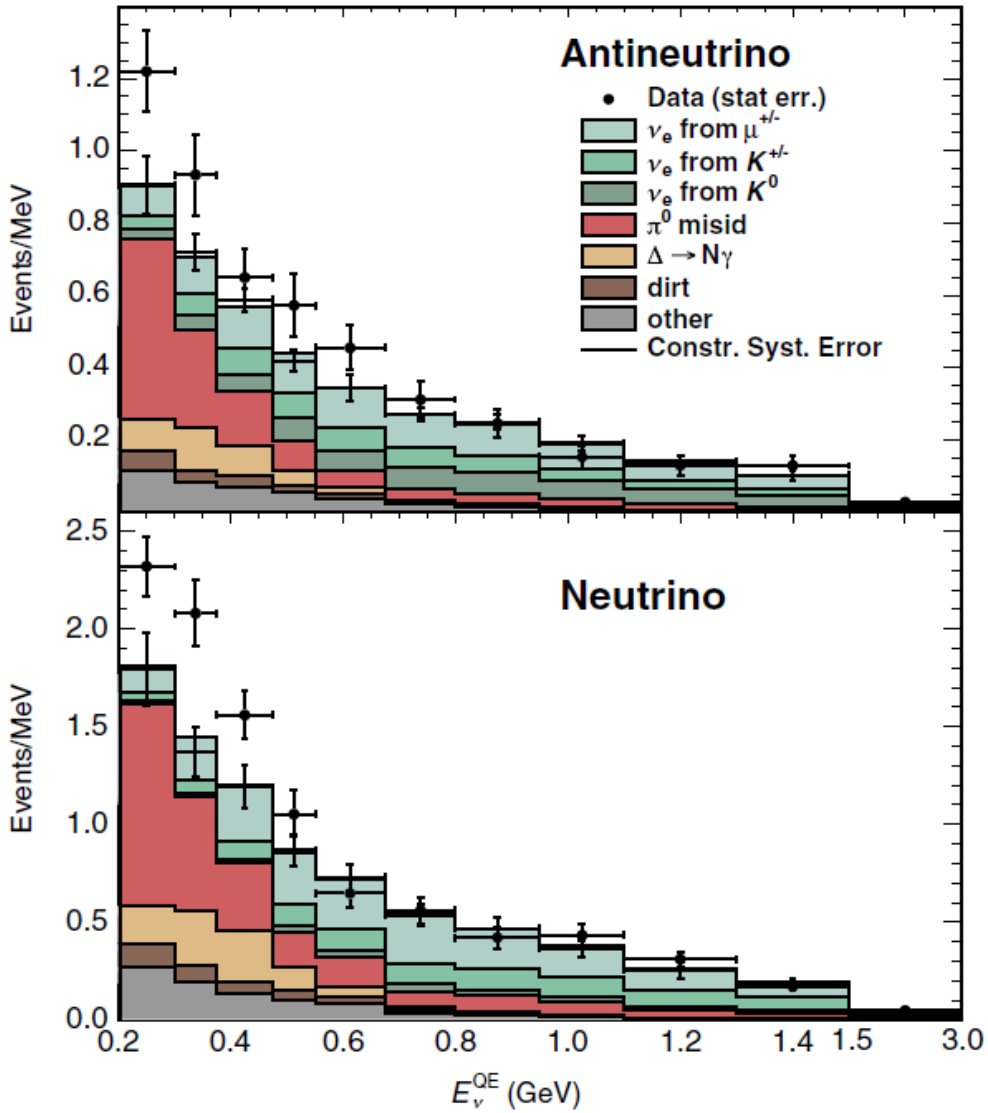
  - Small cross section (weak & e.m.)

but

  - Important background for $\nu_\mu \rightarrow \nu_e$ studies (θ_{13} , δ) if γ is misidentified as $e^{\pm}$ from CCQE $\nu_e\, n \rightarrow e^-\, p$ or $\bar{\nu}_e\, p \rightarrow e^+\, n$

NCγ

- Photon emission in NC interactions:



$\gamma\, N$

$\gamma\, X$ $\leftarrow$ incoherent

$\gamma\, A$ $\leftarrow$ coherent

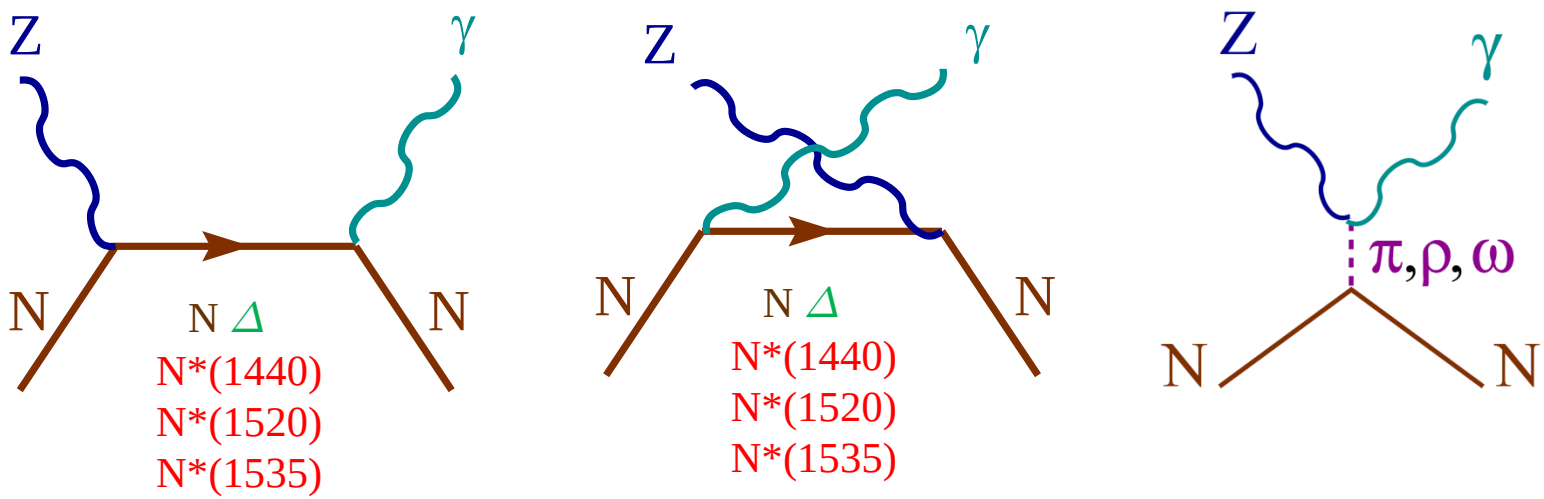
studies (θ_{13} , δ) if γ is misidentified

r $\bar{\nu}_e\, p \rightarrow e^+\, n$

Aguilar-Arevalo et al., PRL110 (2013) 161801

NCγ

- Feynman diagrams:

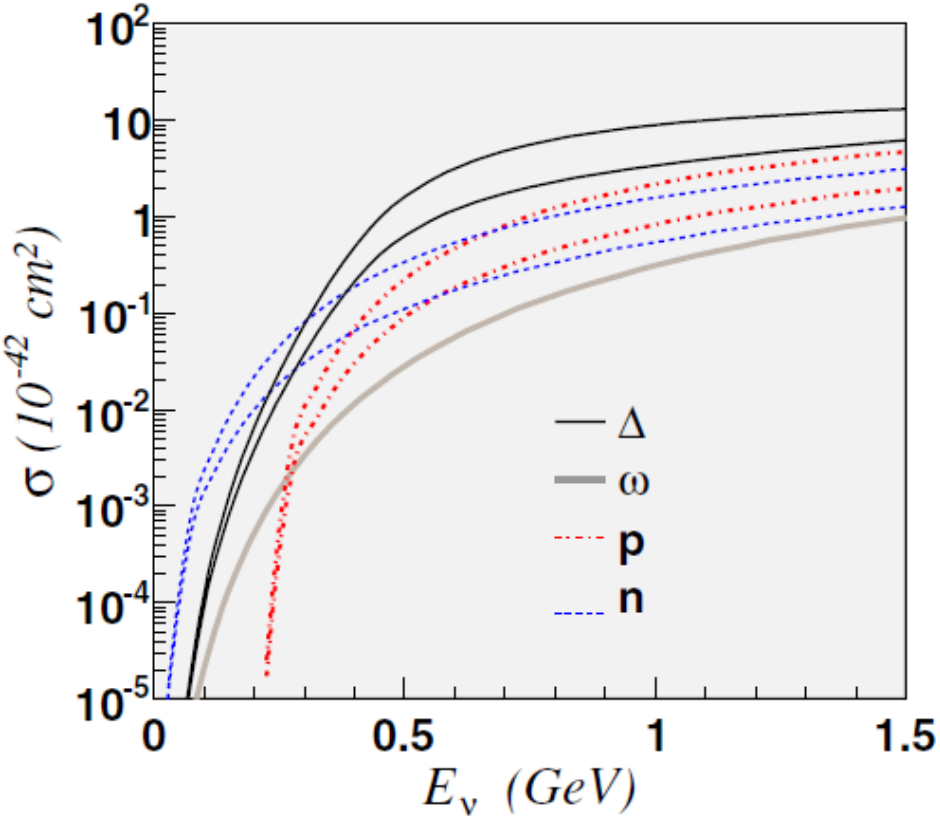


R. Hill, PRD 81 (2010)
Zhang & Serot, PRC 86 (2012)
Wang, LAR, Nieves, PRC 89 (2014)

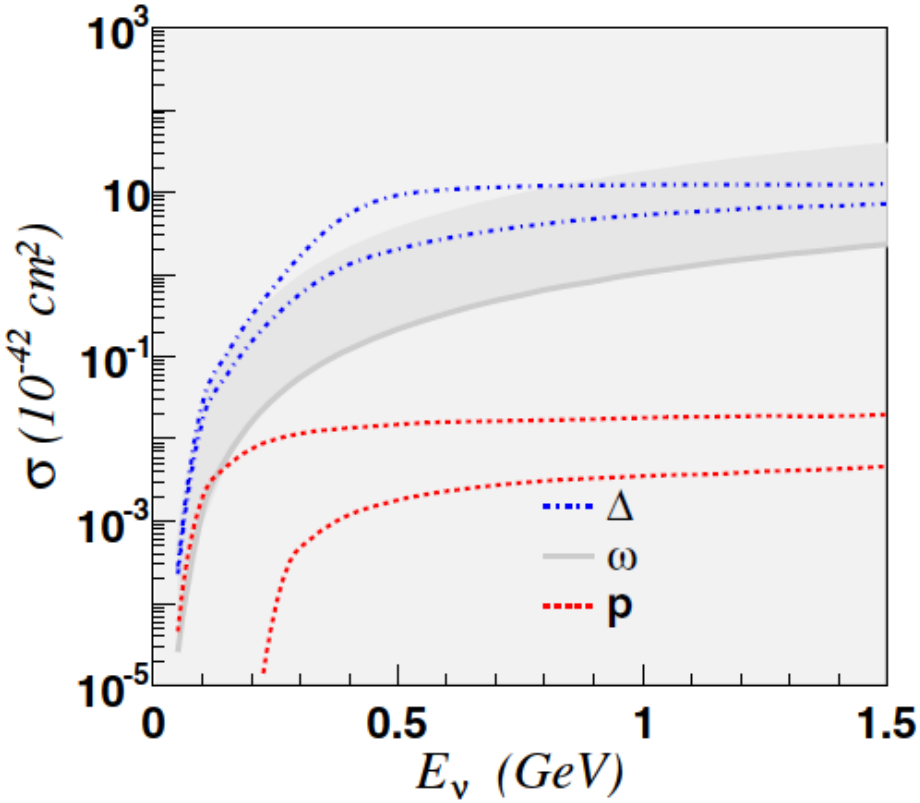
NCγ

- R. Hill, PRD 81 (2010)

$$\nu(\bar{\nu})\, N \rightarrow \nu(\bar{\nu})\, \gamma\, N$$



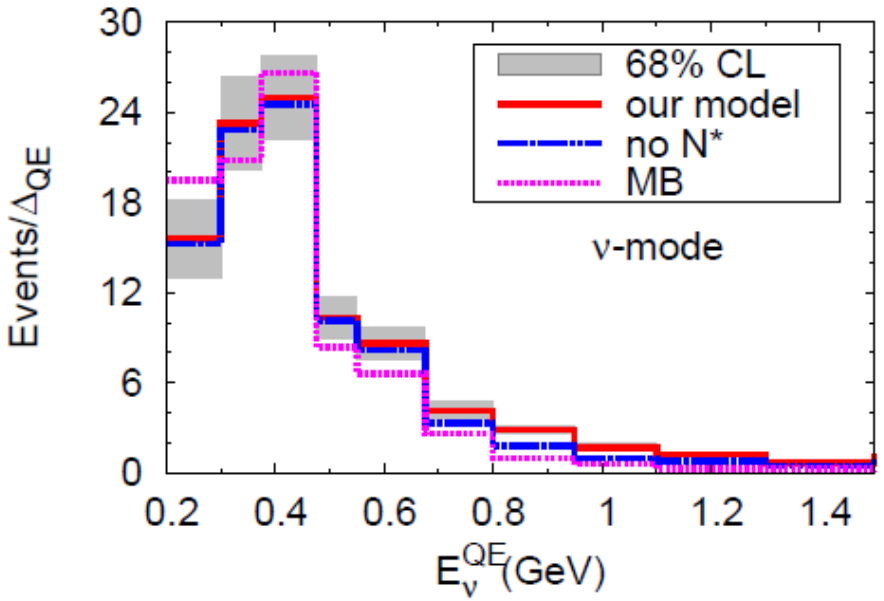
$$\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, A$$

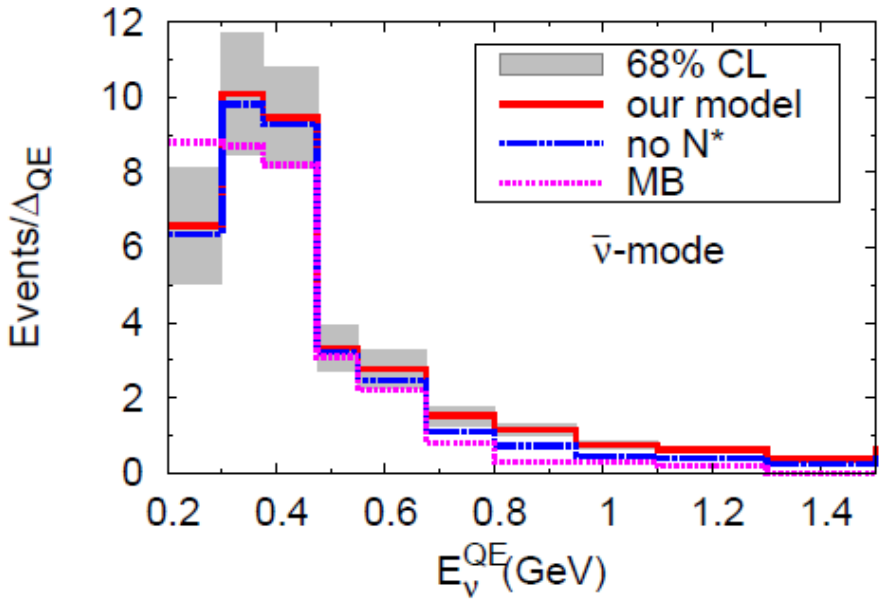


- The ω exchage contribution is very small

NCγ events at MiniBooNE

- Comparison to the MiniBooNE estimate
  - Resonance model (R&S) tuned to π production data
  - Only R -> N γ



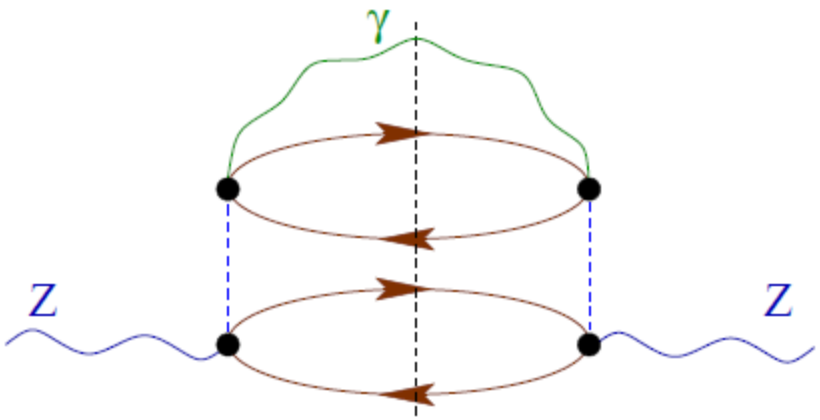


E. Wang, LAR, J. Nieves, PLB 740 (2015)

- NCγ : insufficient to explain the excess of e-like events at MiniBooNE

NCγ events at MiniBooNE

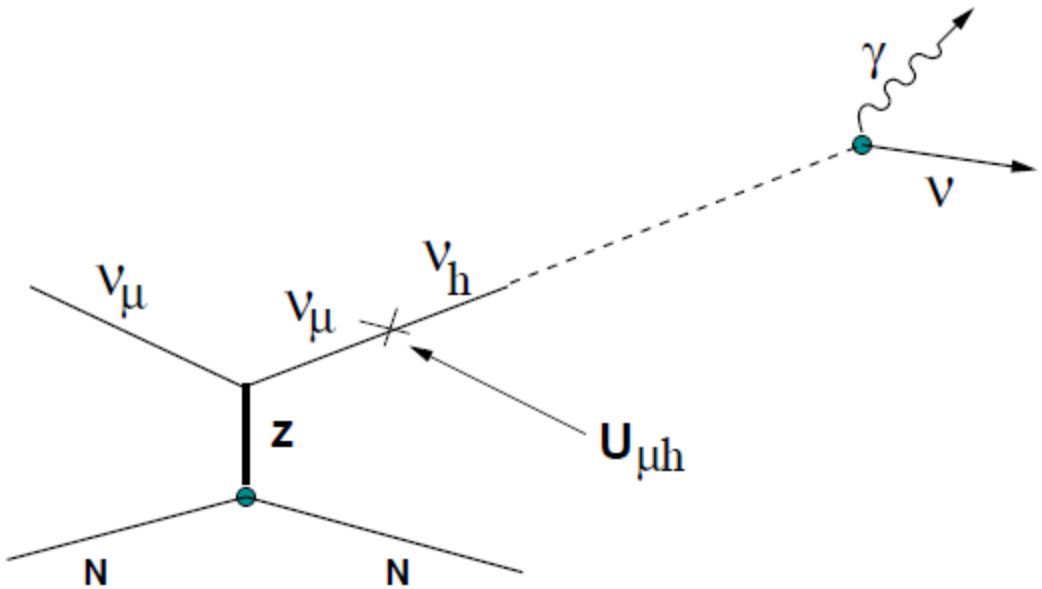
- Multi-nucleon contributions
  - $Z\ NN \to NN\ \pi$, $Z\ NN \to NN\ \gamma$



  - Potentially important but unlikely to be the full solution

e-like events at MiniBooNE

- Oscillations: not explained by 1, 2, 3 families of sterile neutrinos J. Conrad et al., Adv. High Energy Phys. 2013, C. Giunti et al., PRD88 (2013)
- Heavy neutrinos S. Gninenko, PRL 103 (2009), M. Masip et al, JHEP 1301 (2013)



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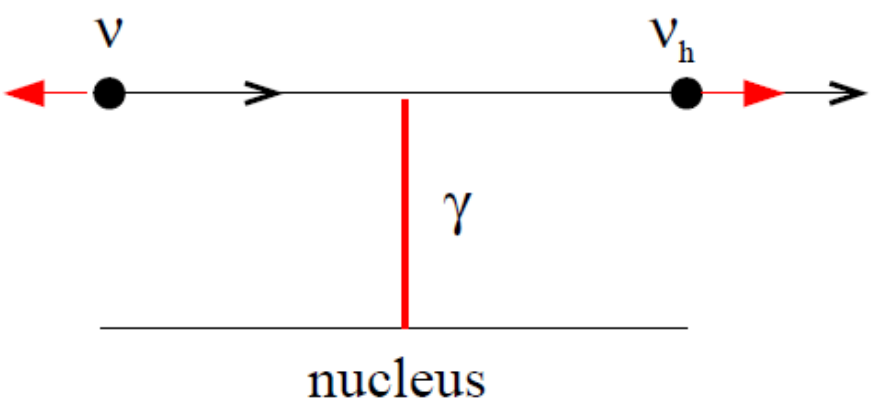
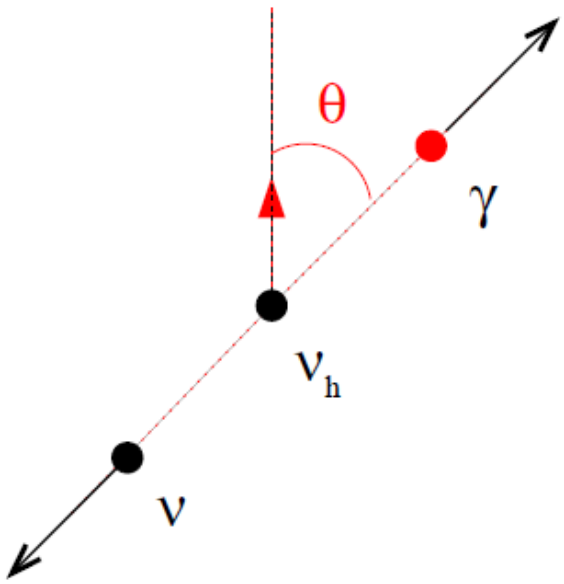
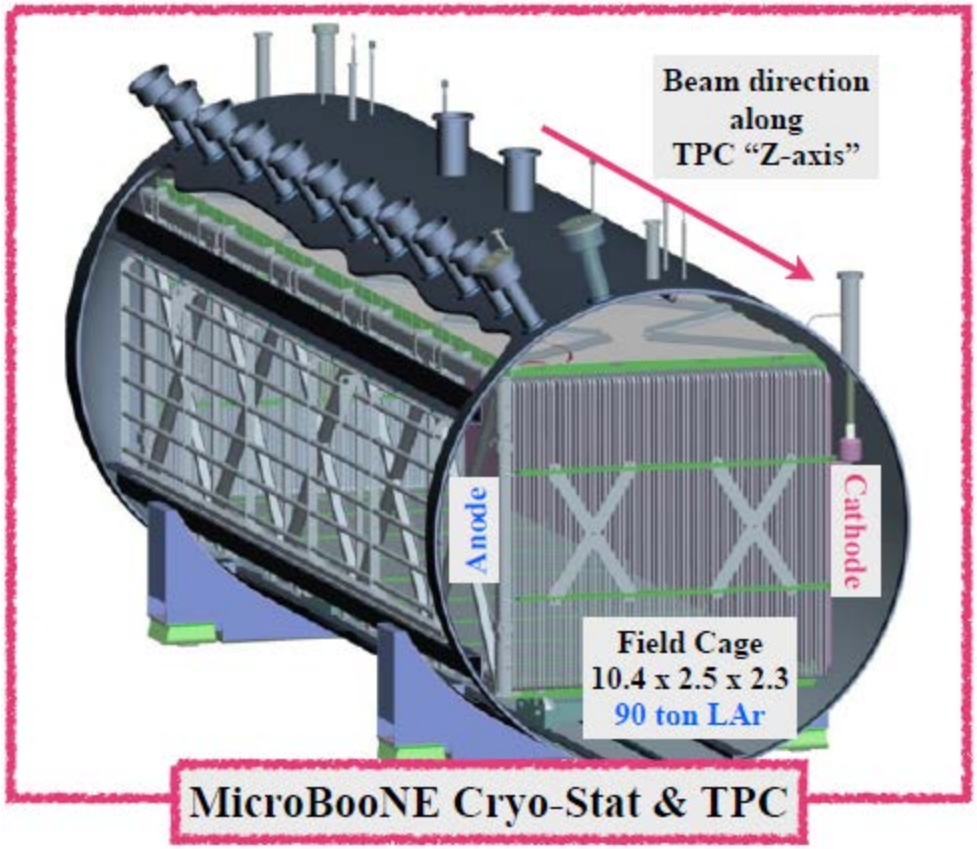




MicroBooNE

- 170 ton LArTPC
- Located along the Booster neutrino beam line
- Distinguishes electrons from photons



Strangenes production

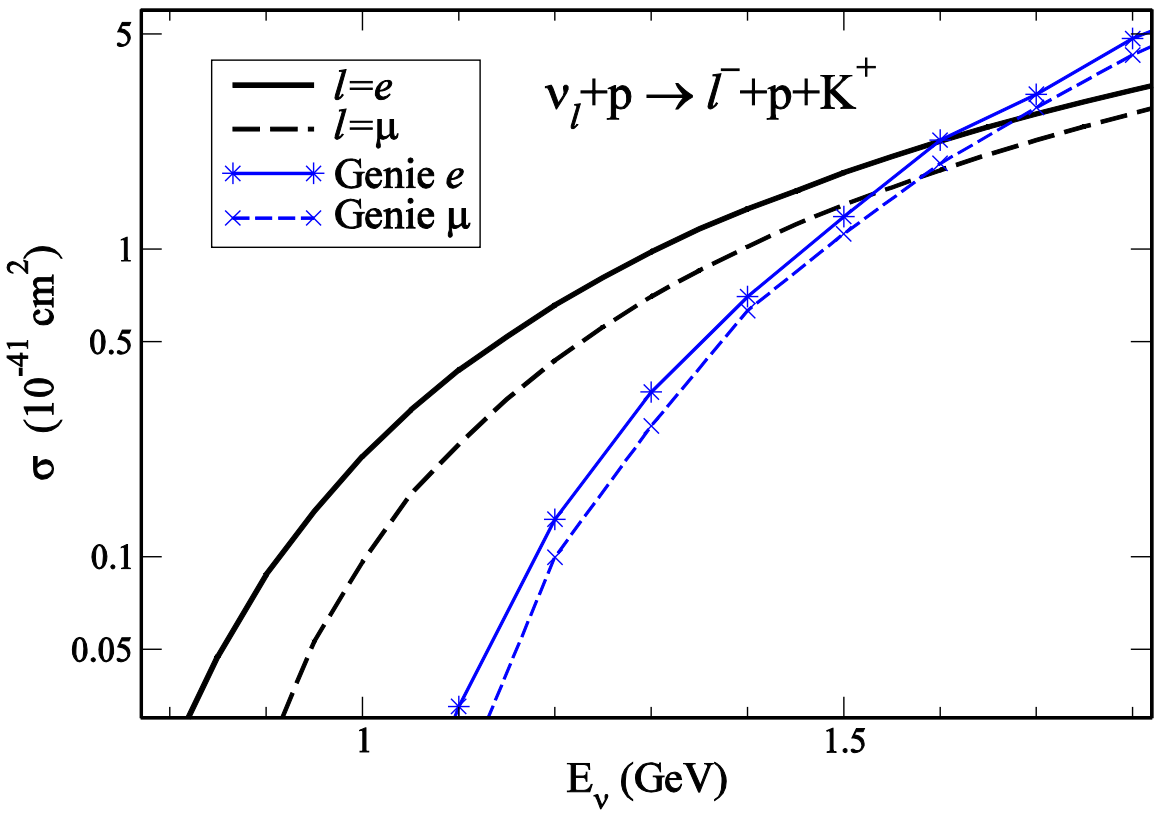
- $\Delta S = 0$ e.g. $\nu_l\, p(n) \to l^-\, K^+\, \Sigma^+(\Lambda)$
- $\Delta S = 1$:
  - Cabibbo suppressed but with lower thresholds than $\Delta S = 0$
  - Kaon:

$$\begin{aligned} \nu_l\, p &\to l^-\, K^+\, p \\ \nu_l\, n &\to l^-\, K^0\, p \\ \nu_l\, n &\to l^-\, K^+\, n \end{aligned}$$

    - Background for proton decay $p \to \nu\, K^+$

Strangenes production

- Microscopic kaon production on the nucleon Rafi Alam et al., PRD82
  - vs $\Delta S = 0$ from GENIE



Strangenes production

- ΔS = -1 :
  - Cabibbo suppressed but with lower thresholds than ΔS = 0
  - Hyperon $\bar{\nu}_l\, p \;\rightarrow\; l^+\, \Sigma^0(\Lambda)$

    $\bar{\nu}_l\, n \;\rightarrow\; l^+\, \Sigma^-$

    - Additional source of pions: Y $\rightarrow$ N π
  - antiKaon: $\bar{\nu}_l\, p \;\rightarrow\; l^+\, K^-\, p$

    $\bar{\nu}_l\, p \;\rightarrow\; l^+\, \bar{K}^0\, n$

    $\bar{\nu}_l\, n \;\rightarrow\; l^+\, K^-\, n$

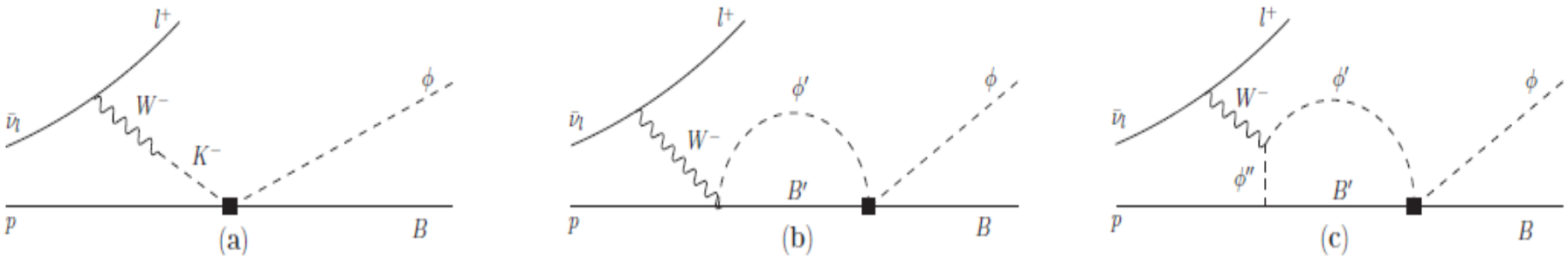
  - $\Sigma\, \pi$: $\bar{\nu}_l\, p \;\rightarrow\; l^+\, \Sigma^0\, \pi^0$

    $\bar{\nu}_l\, p \;\rightarrow\; l^+\, \Sigma^+\, \pi^-$

    $\bar{\nu}_l\, p \;\rightarrow\; l^+\, \Sigma^-\, \pi^+$

Strangeness production

- $\bar{\nu}_l \, p \to l^+ \, \Sigma \, \pi$
- Ren, Oset, LAR, Vicente Vacas, arXiv:1501.04073



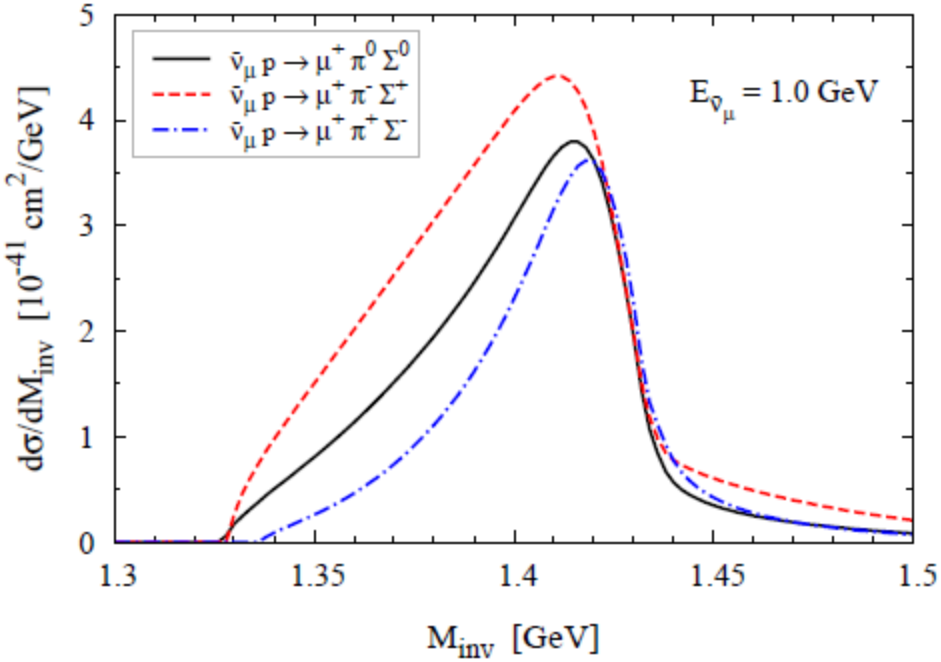
- T: Solution of the Bethe-Salpeter eq. in coupled channels

$$T = V + VGT = [1 - VG]^{-1} V$$

- V: from leading order chiral Lagrangian

Strangeness production

- $\bar{\nu}_l\, p \to l^+ \Sigma\, \pi$
- Ren, Oset, LAR, Vicente Vacas, arXiv:1501.04073
- $\Lambda(1405)$ dynamically generated
- Two poles:
  - M$\approx$ 1385 MeV, $\Gamma \approx$ 150 MeV
  - M$\approx$ 1420 MeV, $\Gamma \approx$ 40 MeV



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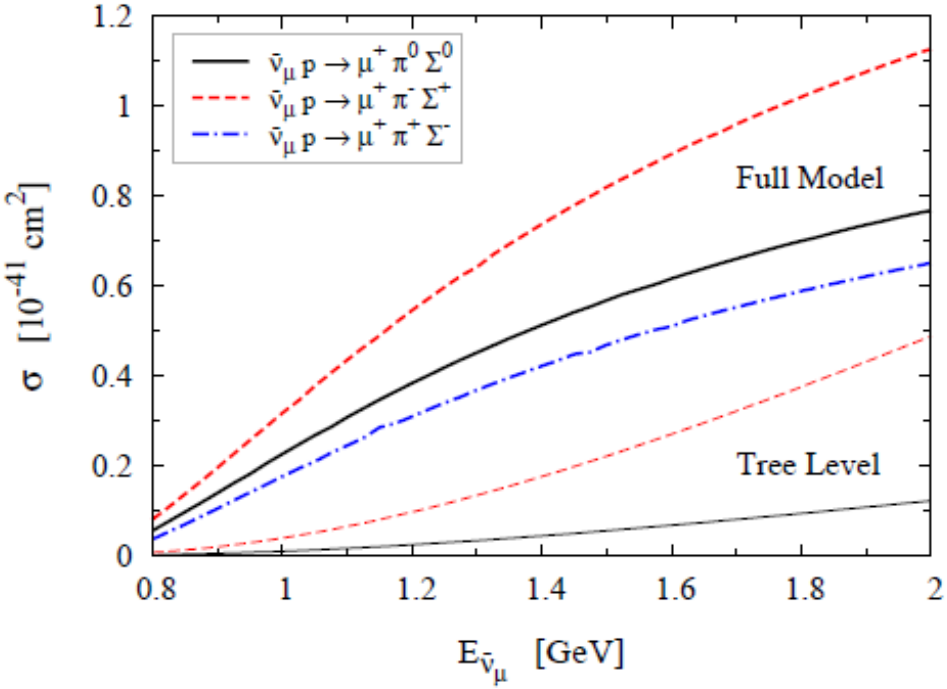
- c. s. enhanced by the resonance



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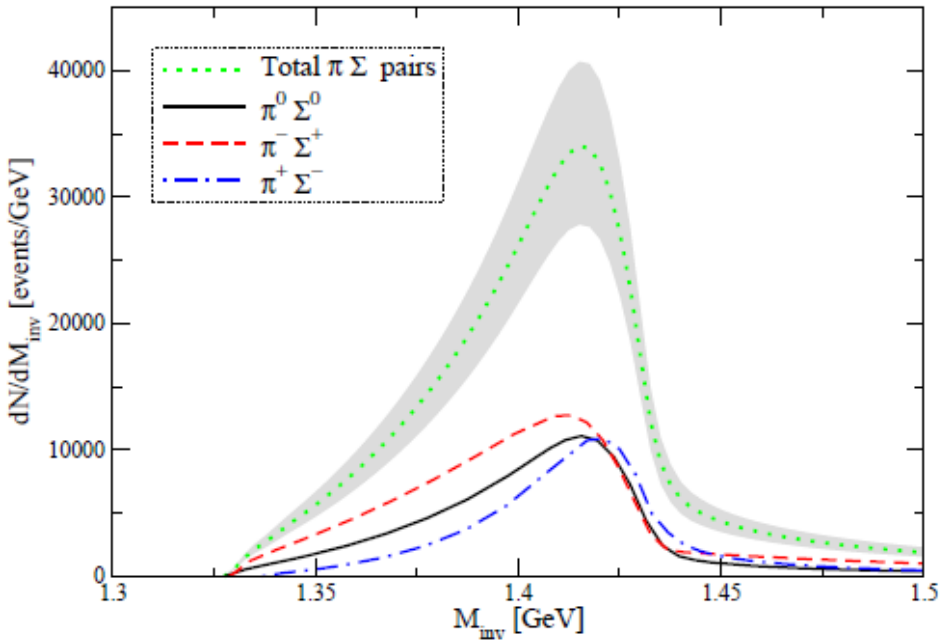
- $\approx$ 2000 events @ MINERvA



Outlook

- ν scattering on nucleons and nuclei is relevant for oscillation studies
- Interesting for hadron and nuclear physics
- Interpretation of experimental results and model testing (tuning) are challenged by
  - Poor knowledge of ν-N cross sections
  - Non-monochromatic beams
  - Nuclear effects/ FSI

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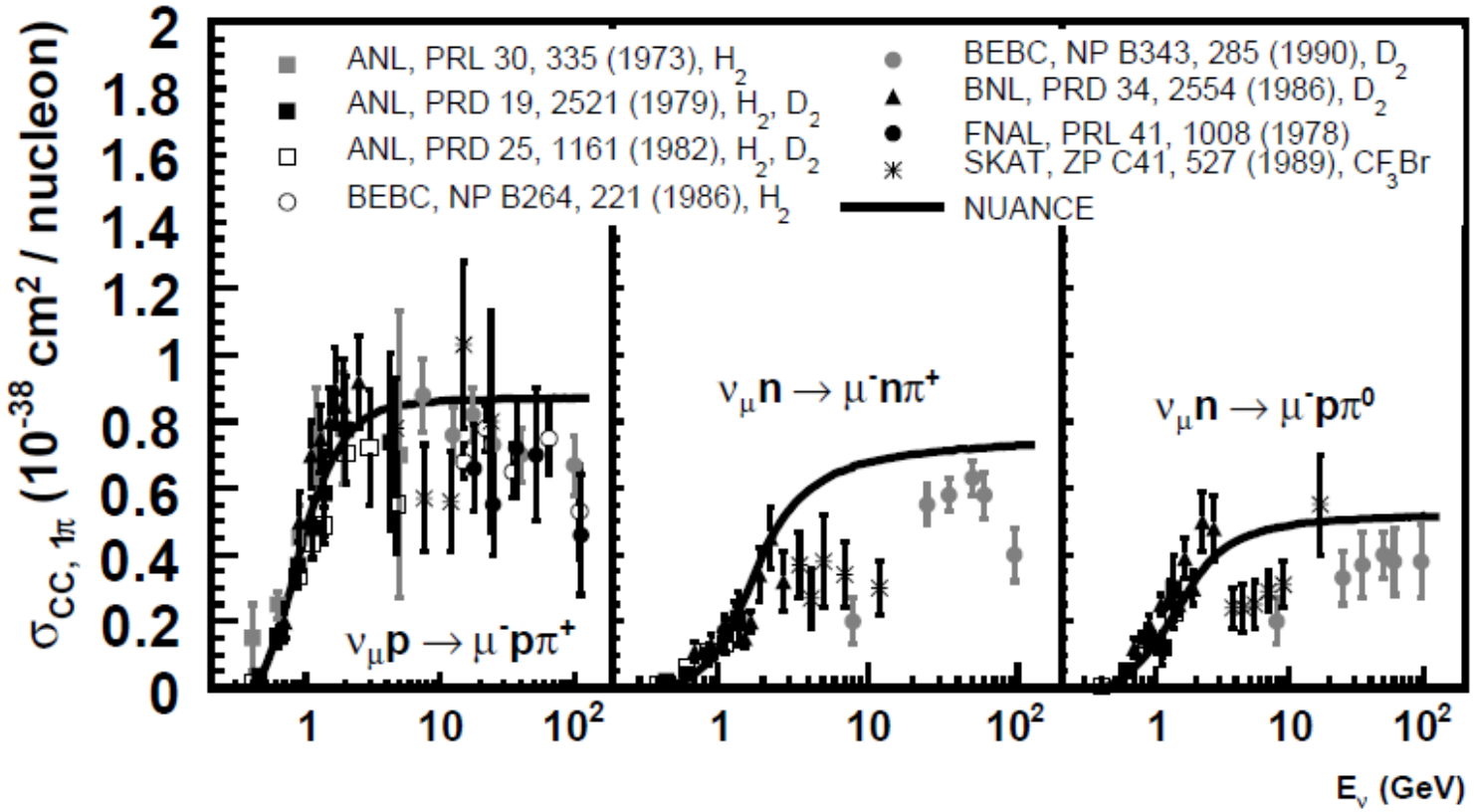
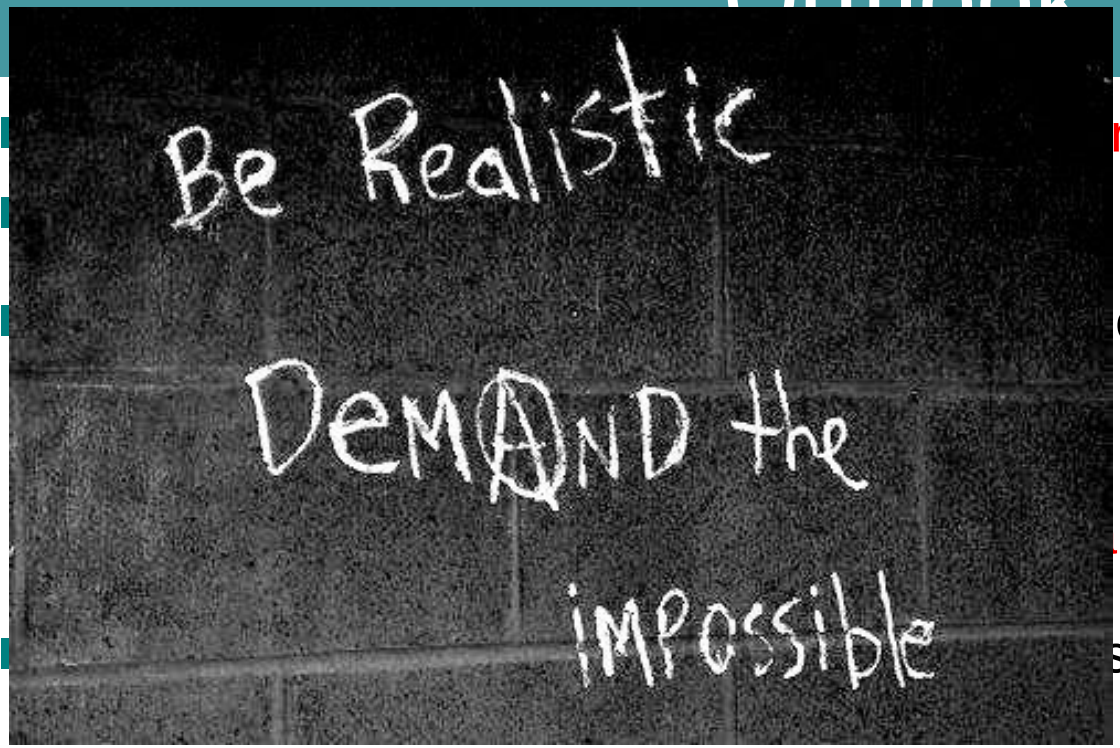


Outlook

- ν scattering on nucleons and nuclei is relevant for oscillation studies
- Interesting for hadron and nuclear physics
- Interpretation of experimental results and model testing (tuning) are challenged by
  - Poor knowledge of ν-N cross sections:
  - new ν-N measurements are highly desirable
- MINERvA: D/H target proposed. Challenge: safety measures
- Bubble chamber @ NuSTORM $\leftarrow$ ideal

Outlook



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