Hadron and Nuclear Physics for Oscillation Experiments

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Introduction

- ν cross sections are crucial to achieve the precision goals of oscillation experiments

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

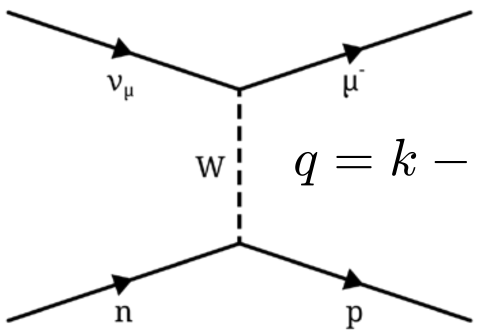
F. Sanchez @ NuPhys2015

- Need for theory?
  - Measurements are not (cannot be) comprehensive
    - the same (semi)-inclusive cross section can correspond to different exclusive final states, depending on the reaction mechanism
    - measurements (partially) rely on simulations ≈ theory to determine efficency, acceptance, ...
  - E_ν is not known: reconstructed using kinematics and/or calorimetry
  - $\sigma(\nu_\mu)$ to $\sigma(\nu_e)$ extrapolations
- Neutrino c.s. mismodeling could lead to unacceptably large systematic uncertainties or biased measurements

Nucleon axial form factor

- Fundamental nucleon property
- Main source of uncertainty for QE scattering on nucleons:

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



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

- Largest contribution at T2K, MicroBooNE
- Used for kinematic E_ν reconstruction:

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

- Input in models of non-resonant inelastic reactions (meson production) and two-nucleon currents

Nucleon axial form factor

- What is known:
  - $F_A(0) = g_A \leftarrow \beta$ decay
  - $F_A(\infty) \sim Q^{-4} \leftarrow$ QCD
- Main source of information: bubble chamber (ANL, BNL, FNAL) data
- Dipole ansatz: Bodek et al., EPJC 53 (2008)

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

- z-expansion: Meyer et al., PRD 93 (2016)
- Neural networks + Bayesian statistics: LAR, Graczyk, Saúl-Sala, PRC 99 (2019)
- All methods obtain similar $F_A(Q^2)$...

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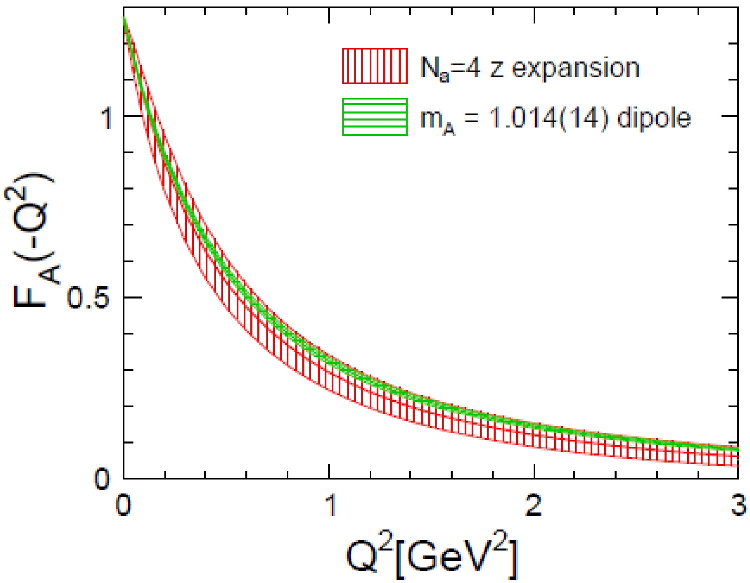
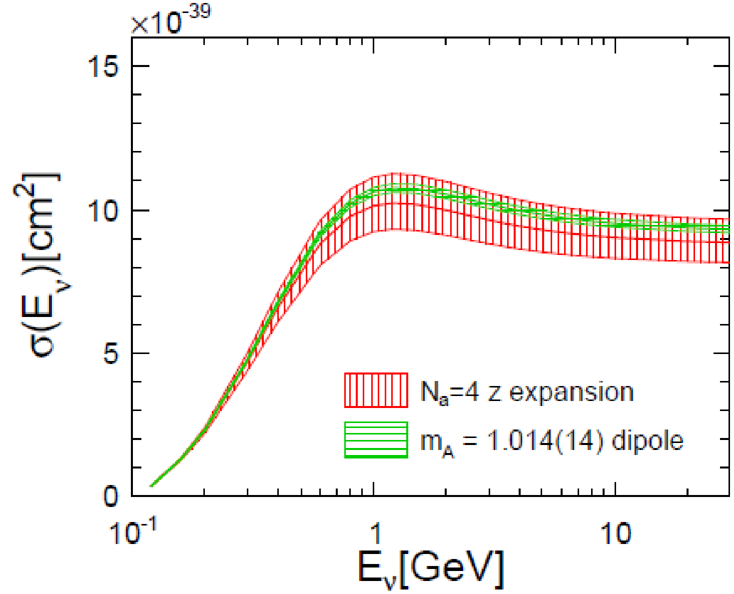
  - $\langle r_A^2 \rangle$ = 0.453(12) fm^2
- z-expansion: Meyer et al., PRD 93 (2016)
  - $\langle r_A^2 \rangle$ = 0.46(22) fm^2
- Neural networks + Bayesian statistics: LAR, Graczyk, Saúl-Sala, PRC 99 (2019)
  - $\langle r_A^2 \rangle$ = 0.471(15) fm^2 $\leftarrow$ ANL only so far
- All methods obtain similar F(Q^2)...
- ... but with different errors

QE scattering on the nucleon

- z-expansion Meyer et al., PRD 93 (2016)

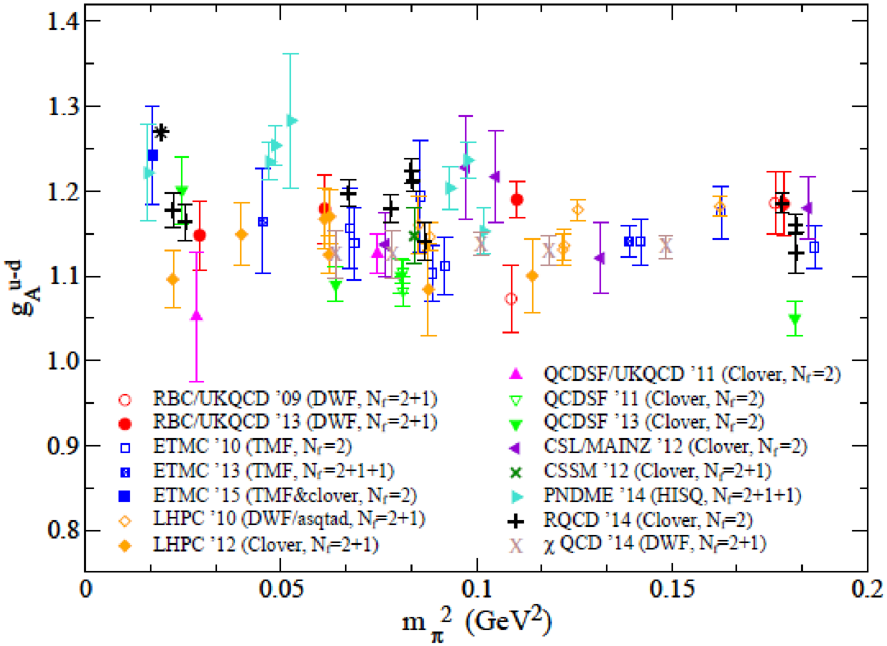




- At $E_\nu \sim 1$ GeV σ(CCQE) has $\approx$ 10 % error
- More precise information about F_A is needed
  - Direct or indirect CCQE measurement on n/p
  - Lattice QCD

F_A & LQCD

- g_A : lower than exp. values have been recurrently obtained



Constantinou, PoS CD15 (2015) 009

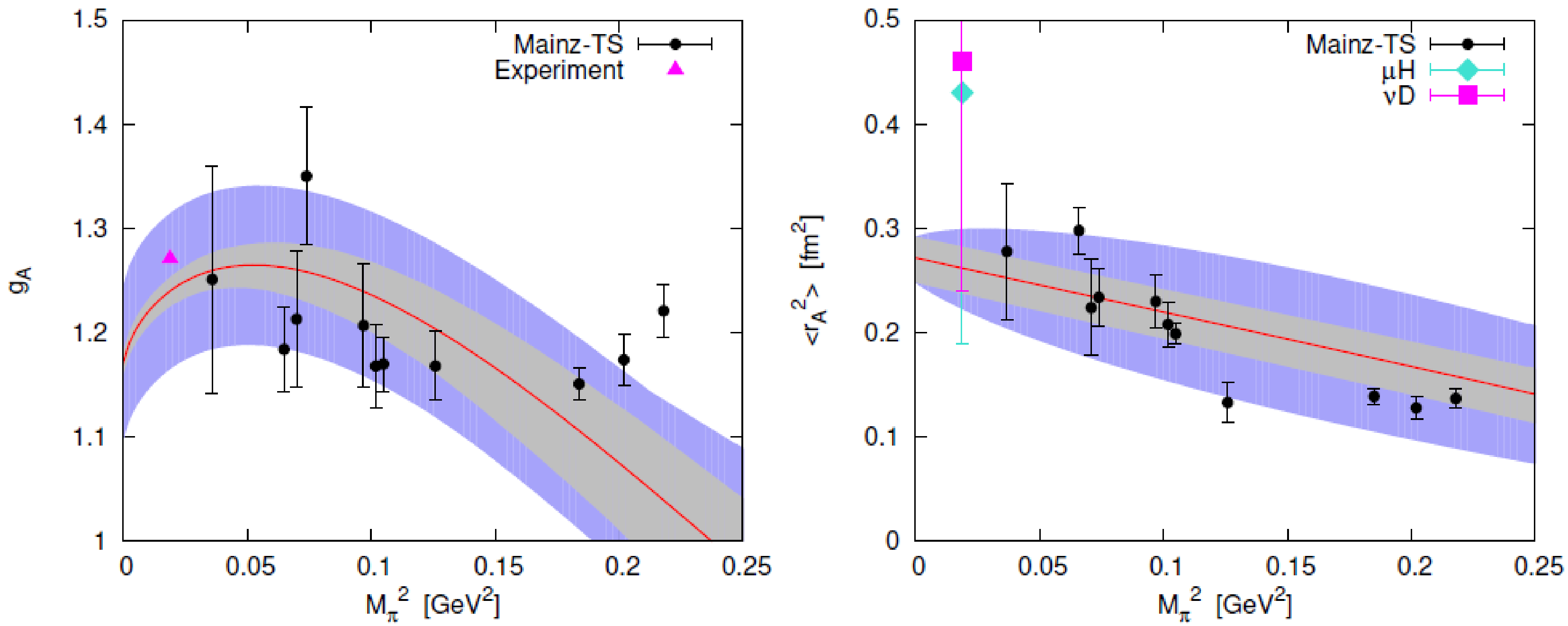
- Recent progress:
  - improved algorithms for a careful treatement of excited states
  - low pion masses

F_A & LQCD

- Recent progress:

  Alexandrou et al., PRD 96 (2017)
  Capitani et al., arXiv:1705.06186
  Gupta et al., PRD 96 (2017)

- Baryon ChPT analysis: Yao, LAR, Vicente Vacas, PRD 96 (2017)
  - $O(p^3)$, $Q^2 < 0.36$ GeV^2, 130 MeV < M_π < 473 MeV, explicit $\Delta(1232)$



  - g_A = 1.237(74) , $<r_A^2>$ = 0.263(38) fm^2

F_A & LQCD

- Recent progress:

  Alexandrou et al., PRD 96 (2017)
  Capitani et al., arXiv:1705.06186
  Gupta et al., PRD 96 (2017)

- More recent progress:
  - A percent-level determination of the nucleon axial coupling from QCD

    Chang et al., Nature 558 (2018)

  - Nucleon form factors at low Q^2 at the physical point

    Shintani et al., PRD 99 (2019)

1π production on the nucleon

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

- CC: $\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+, \quad \overline{\nu}_\mu\, p \rightarrow \mu^+\, p\, \pi^-$
  $\nu_\mu\, n \rightarrow \mu^-\, p\, \pi^0, \quad \overline{\nu}_\mu\, p \rightarrow \mu^+\, n\, \pi^0$
  $\nu_\mu\, n \rightarrow \mu^-\, n\, \pi^+, \quad \overline{\nu}_\mu\, n \rightarrow \mu^+\, n\, \pi^-$
  - source of CCQE-like events (in nuclei)
  - needs to be subtracted for a good E_ν reconstruction
- NC: $\nu_\mu\, p \rightarrow \nu_\mu\, p\, \pi^0, \quad \overline{\nu}_\mu\, p \rightarrow \overline{\nu}_\mu\, p\, \pi^0$
  $\nu_\mu\, p \rightarrow \nu_\mu\, n\, \pi^+, \quad \overline{\nu}_\mu\, n \rightarrow \overline{\nu}_\mu\, n\, \pi^0$
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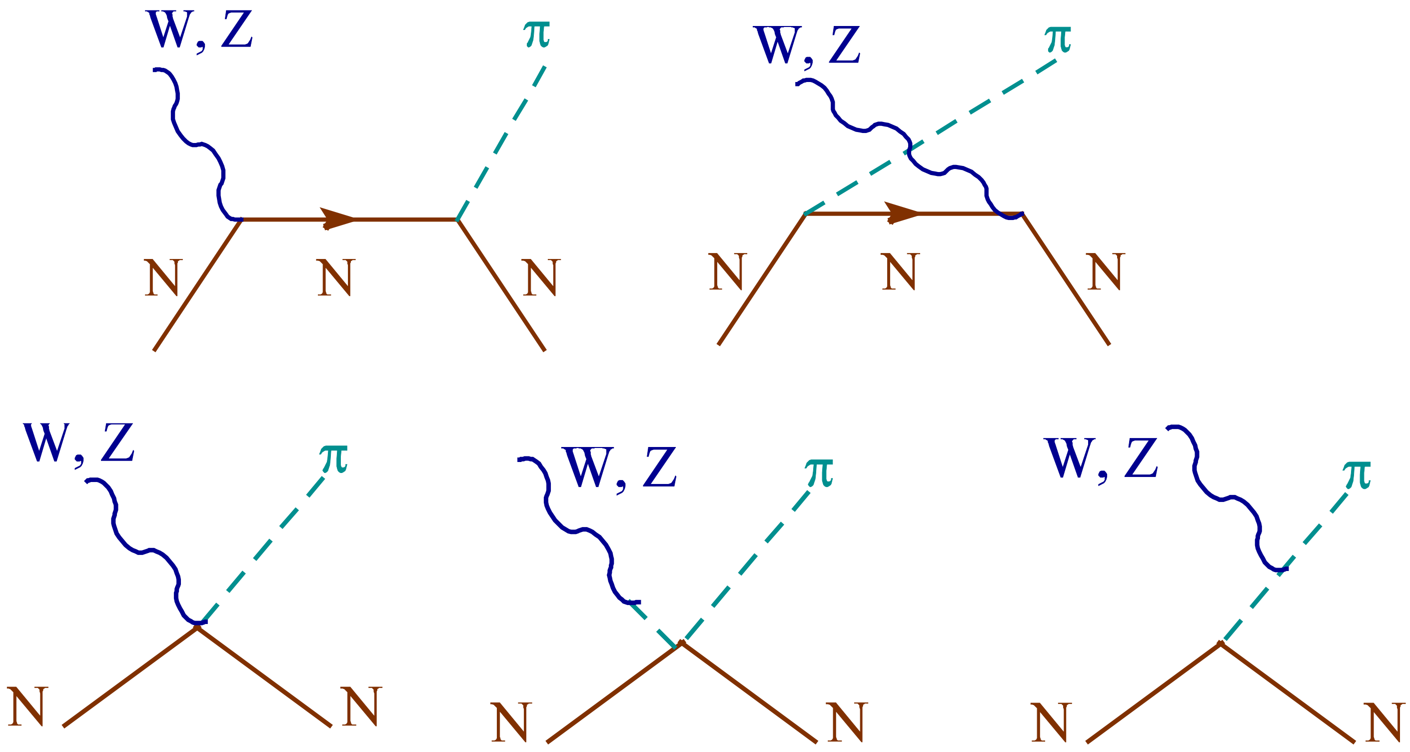
  $\nu_\mu\, n \rightarrow \nu_\mu\, p\, \pi^-, \quad \overline{\nu}_\mu\, n \rightarrow \overline{\nu}_\mu\, p\, \pi^-$
  - e-like background to $\nu_\mu \rightarrow \nu_e$ (T2K, NOvA)

1π production on the nucleon

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

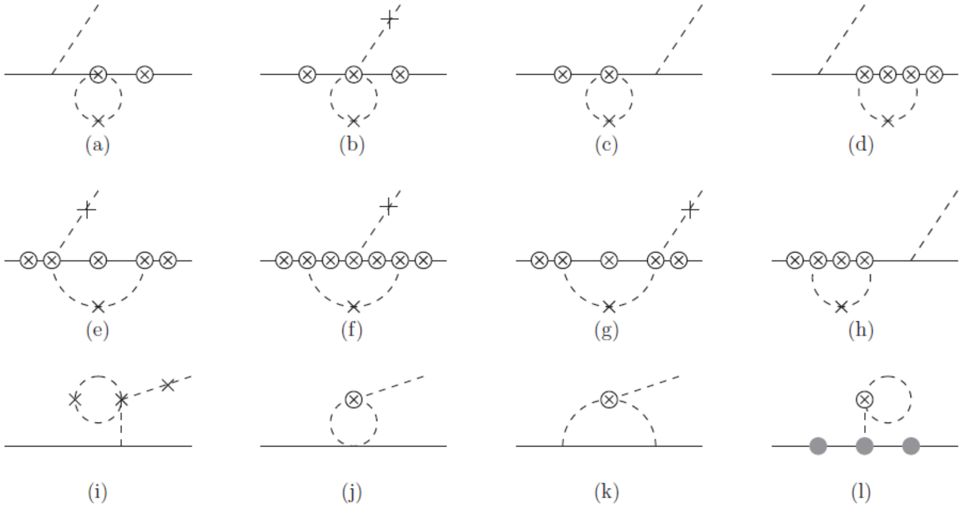
- From Chiral symmetry:



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

Weak pion production in ChPT

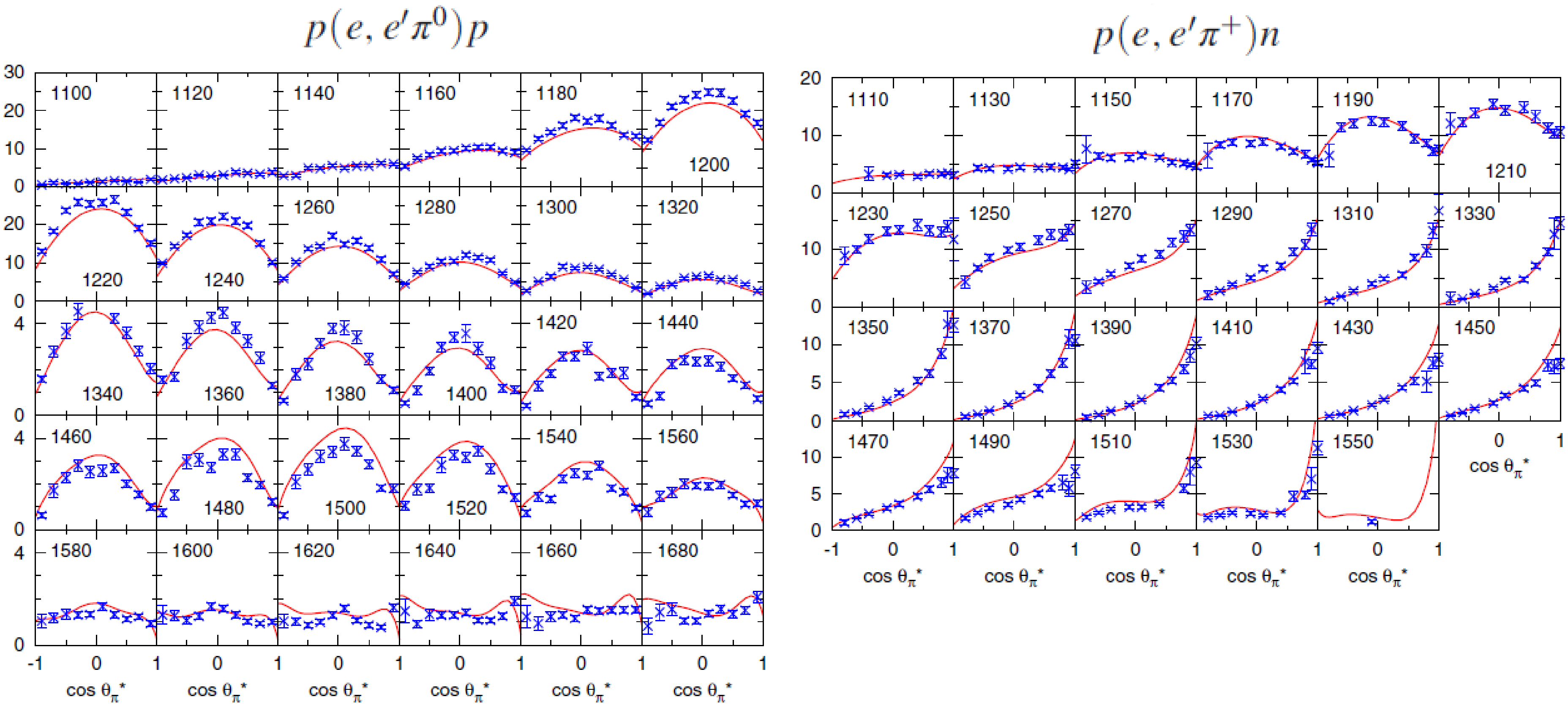
- First comprehensive study in ChPT
- Yao, LAR, Hiller, Vicente Vacas, PRD 98 (2018);
  Yao, LAR, Vicente Vacas, PLB 794 (2019)
- EOMS, explicit $\Delta(1232)$, $O(p^3)$ in the δ-counting: $\delta = m_\Delta - m_N \sim O(p^{1/2})$



- LECs : 22 in total
  - 7 unknown (not very relevant)
    - 4 can be extracted from pion electroproduction
    - information about remaining 3 could be obtained from new close-to-threshold measurements of ν-induced π production on protons
- Valid only close to threshold
- Benchmark for phenomenological models

1π production on the nucleon

- Pheno models rely on (non-ν) data as input and/or validation
  - Vector current can be constrained with $\gamma N \to N \pi$, $e N \to e' N \pi$



- e.g. Dynamical Coupled Channel (DCC) Model Nakamura et al., PRD92 (2015)

1π production on the nucleon

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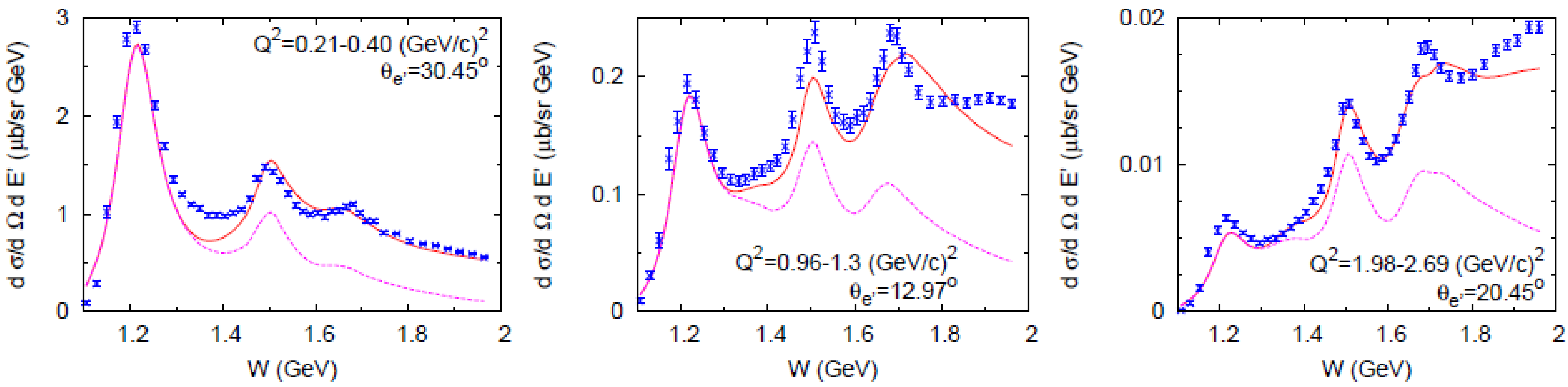
  - Axial current at $q^2 \to 0$ can be constrained with $\pi N \to N \pi$ (PCAC)

$$\left.\frac{d\sigma_{CC\pi}}{dE_l d\Omega_l}\right|_{q^2=0} = \frac{G_F^2 V_{ud}^2}{2\pi^2} \frac{2 f_\pi^2}{\pi} \frac{E_l^2}{E_\nu - E_l} \sigma_{\pi N}$$



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  - Very limited information about the axial current at $q^2 \neq 0$
    - Some on N-Δ(1232) from ANL and BNL data on

$$\nu_\mu \, d \to \mu^- \, \pi^+ \, p \, n$$

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

$M_{A\,\Delta}$ = 0.95 $\pm$ 0.06 GeV

LAR, Hernandez, Nieves, Vicente Vacas, PRD93(2016)

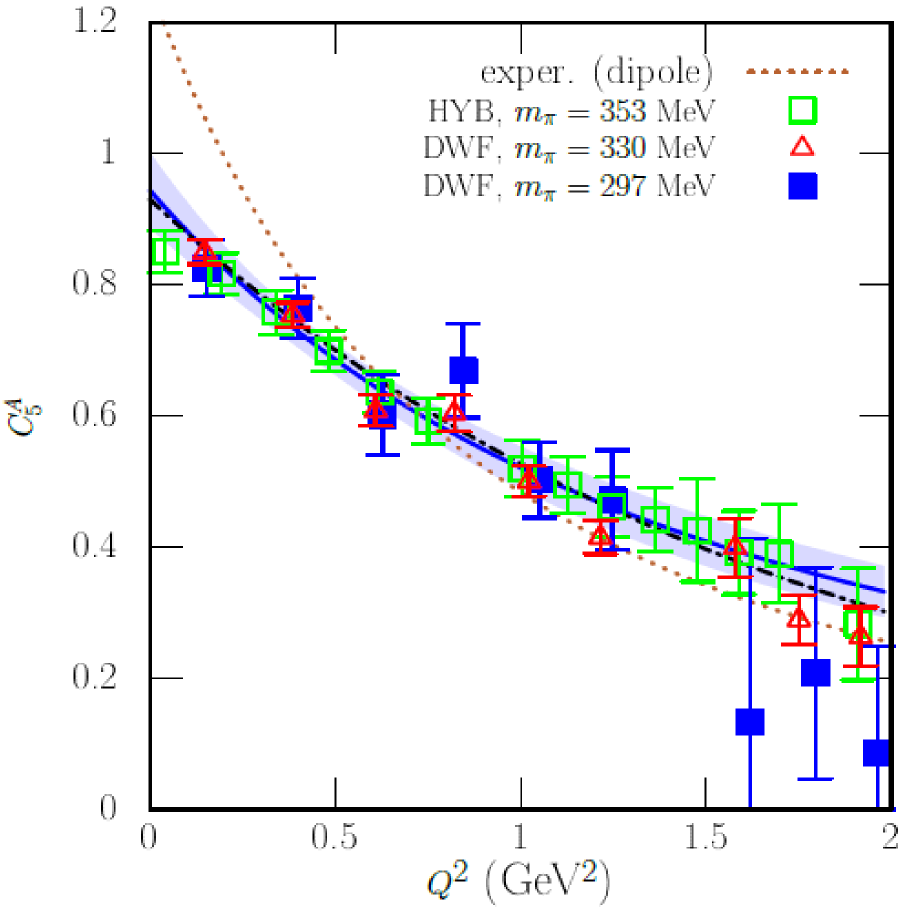
Hernandez, Nieves, PRD 95 (2017)

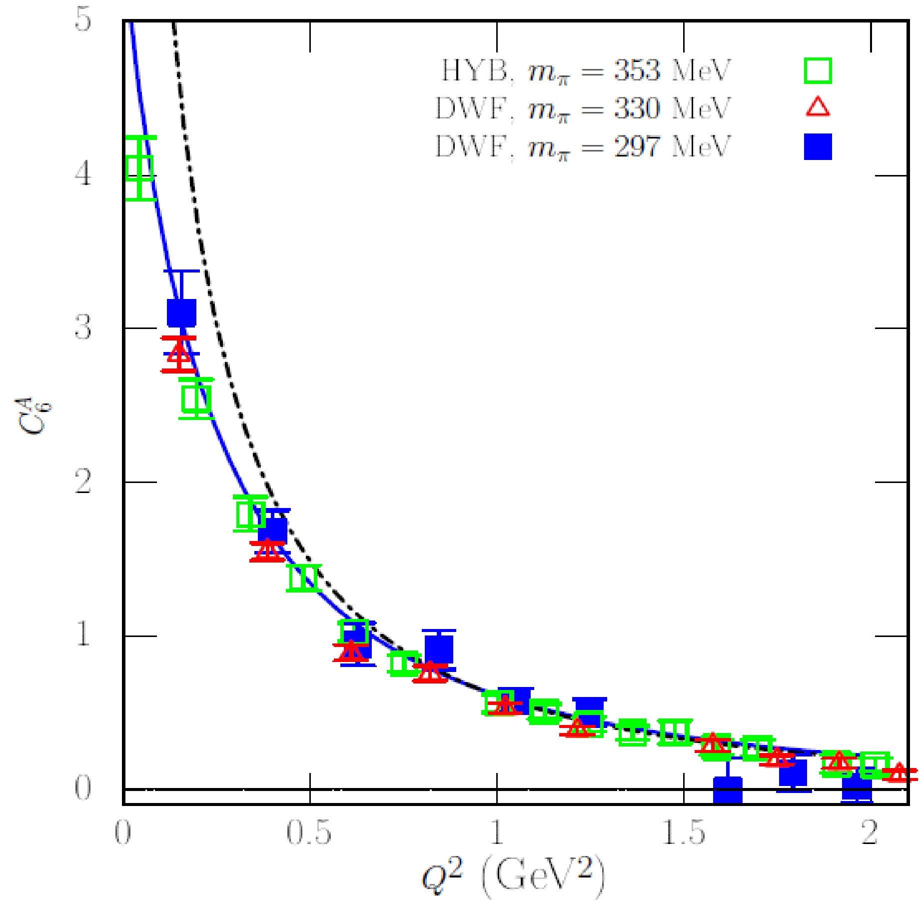
    - Little (no) sensitivity to heavier baryon resonances
    - Lattice QCD

Inelastic form factors & LQCD

- N-Δ axial form factors in LQCD

  Alexandrou et al., PRD83 (2011)





"The Δ is hard enough..." C. Morningstar @ NSTAR 2019

1π production on the nucleon

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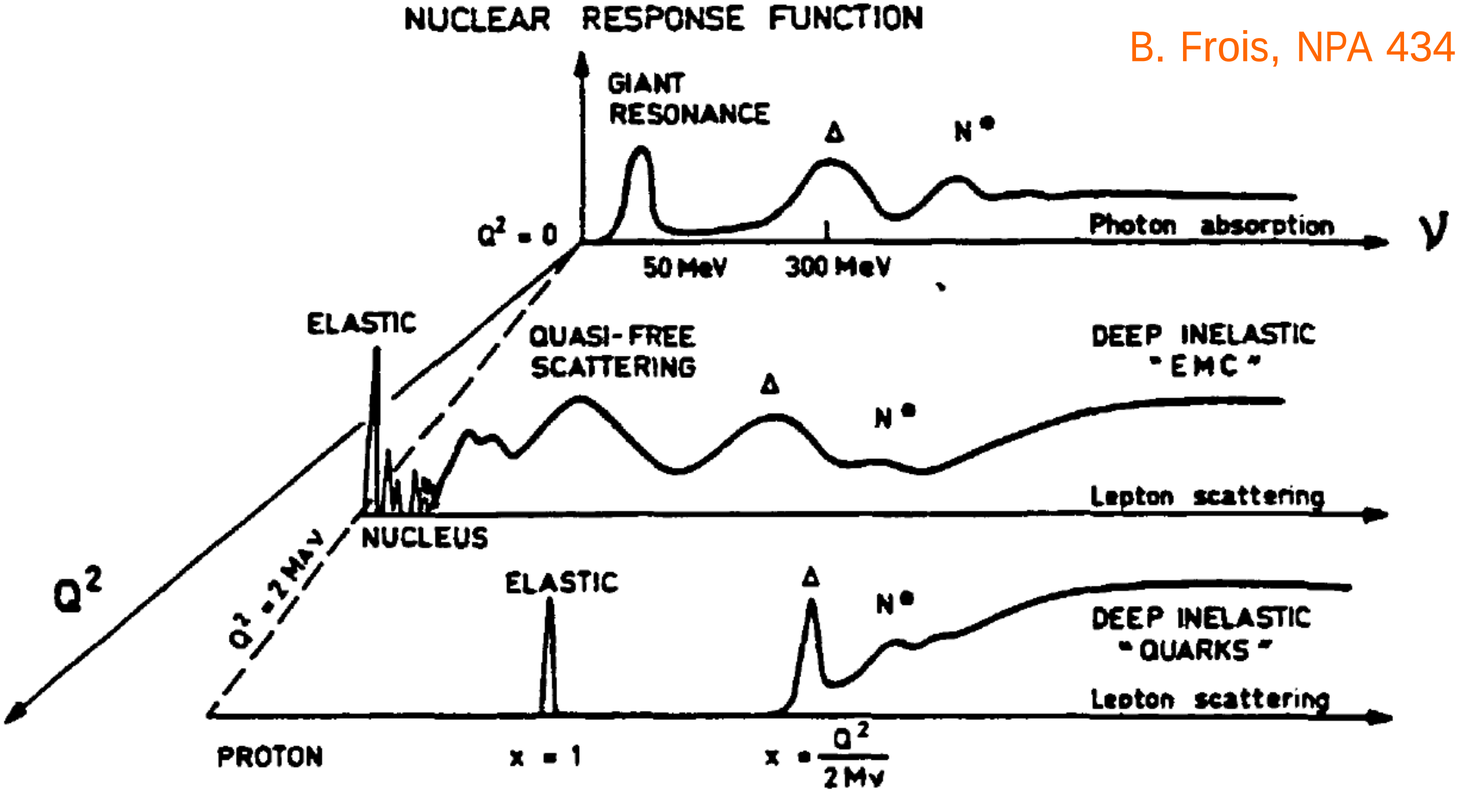
$$\nu_\mu d \to \mu^- \pi^+ p n$$

    - Little (no) sensitivity to heavier baryon resonances
    - Lattice QCD
    - Direct or indirect CC1π measurement on n/p
    - There are hints (T. Sato @ ECT* 2019) that a q^2 dependence similar to the one exhibited by vector form factors might be more realistic

Neutrino interactions on nuclei

- Multiscale (even at a given E_ν), multi-nucleon problem

B. Frois, NPA 434 (1985)

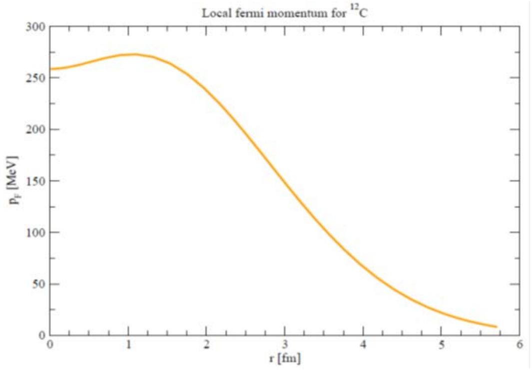


- Shell structure, collective excitations, QE peak, ...
- initial state description: non-relativistic
- final state interactions: (relativistic) NN, πN, ...

QE scattering

Initial nucleon:

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



- (Relativistic) mean field potential
  - Schrödinger/Dirac eq. ⇒ bound-state wave functions

- Spectral function

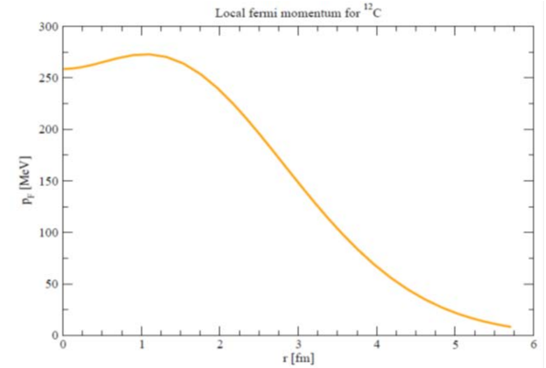
$$\mathcal{A}(p) = \mp\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(p)}{[p^2 - M^2 - \mathrm{Re}\Sigma(p)]^2 + [\mathrm{Im}\Sigma(p)]^2}$$

  - ImΣ = 0 ⇒ mean-field approximation
  - ImΣ ⇔ NN interactions ⇒ short-range correlations

QE scattering

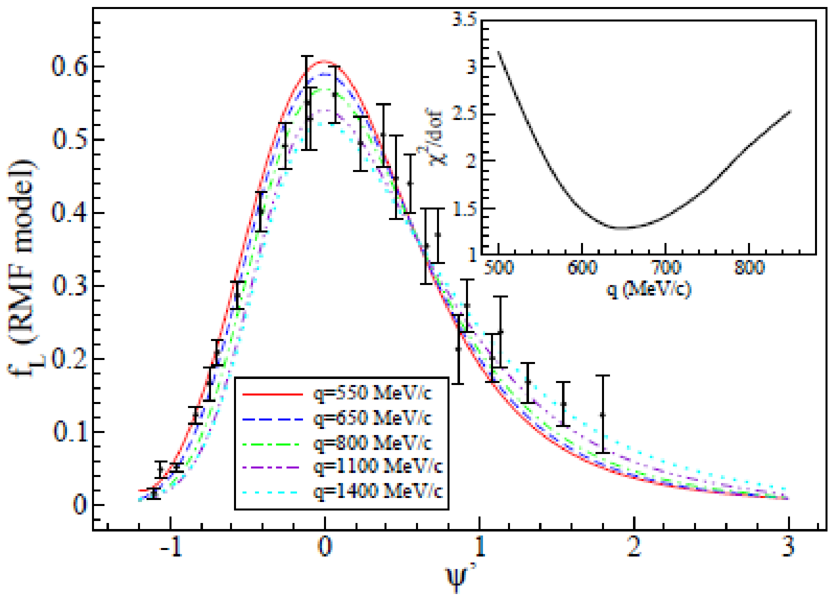
Final nucleon:

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



- Plain waves
- Distorted waves
  - Schrödinger/Dirac eq. $\Rightarrow$ continuum wave functions
  - Relativistic mean field for both initial and final nucleons $\Rightarrow$ realistic scaling function

R. Gonzalez et al., PRC 94 (2014)



QE scattering

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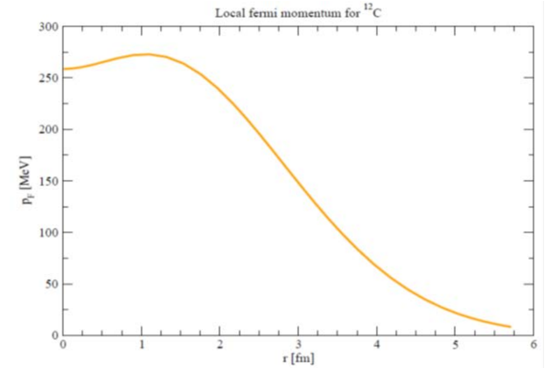
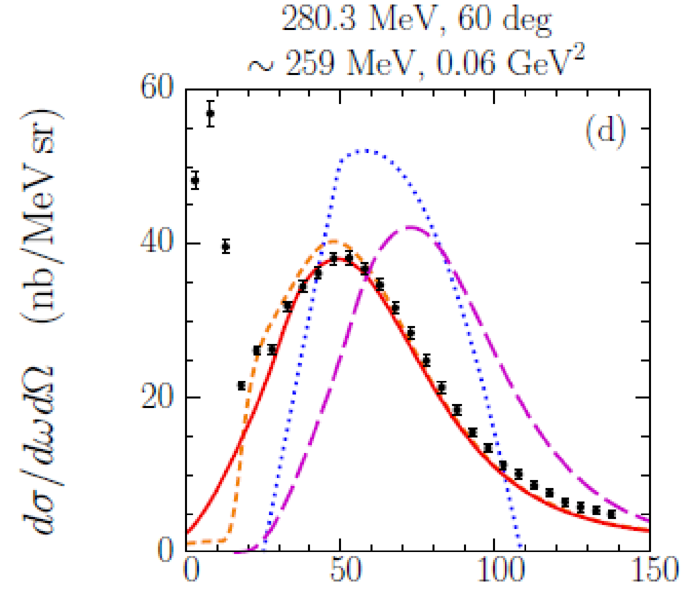
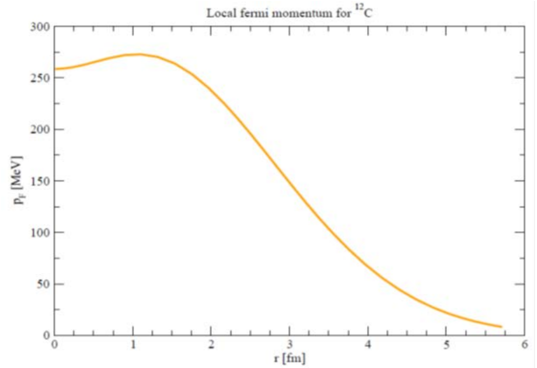


- Plain waves
- Distorted waves
  - Schrödinger/Dirac eq. $\Rightarrow$ continuum wave functions
- Approximate spectral functions
  - Improves the description of (e,e') at low-momentum transfers

    Ankowski et al., PRD 91 (2015)



QE scattering



Final nucleon:

- Local Fermi Gas
  - Pauli blocking: $p_F(r) = [\frac{3}{2}\pi^2\rho(r)]^{1/3}$
- Plain waves
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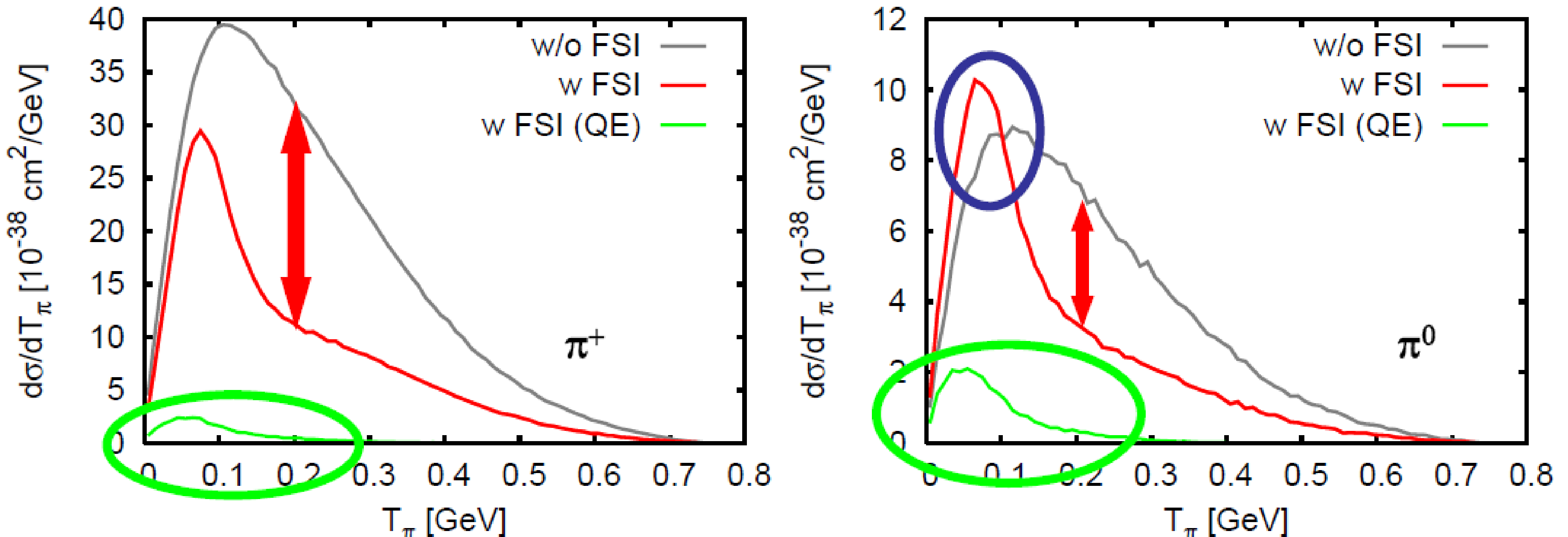
Exclusive final states:

- QM: Distorted waves with complex optical potentials: 1N knockout
- Semi-classical:
  - Cascade: straightline trajectories + NN elastic and inelastic collisions
  - Transport (GiBUU): trajectories in a (x,p) dep. potential + NNcollisions

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



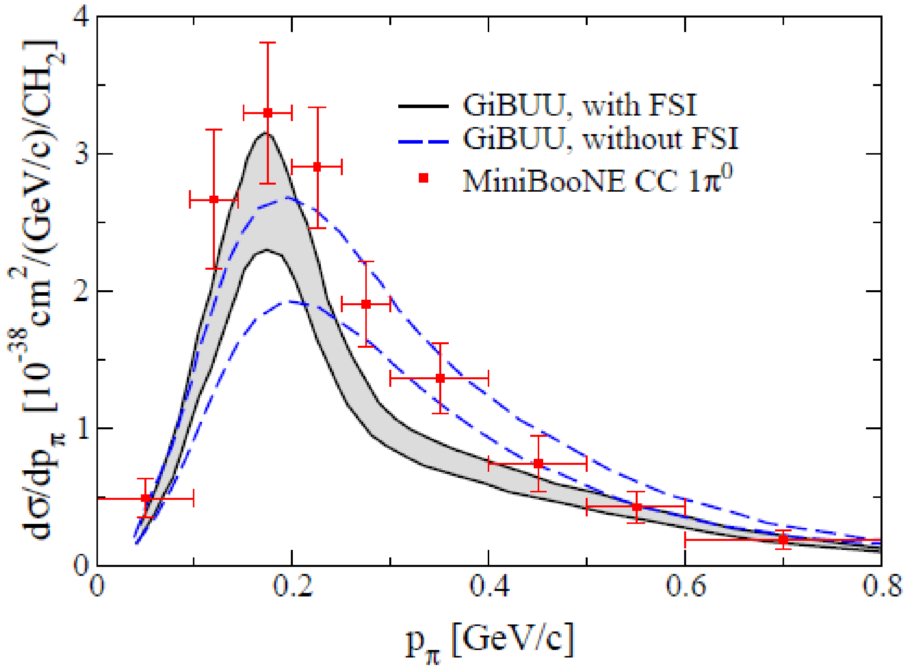
$$\nu_\mu + {}^{56}Fe \to \mu^- \, \pi \, X \quad E_\nu = 1 \text{ GeV}$$

π production on ^{12}C

Comparison to MiniBooNE:

Lalakulich, Mosel, PRC87 (2013)

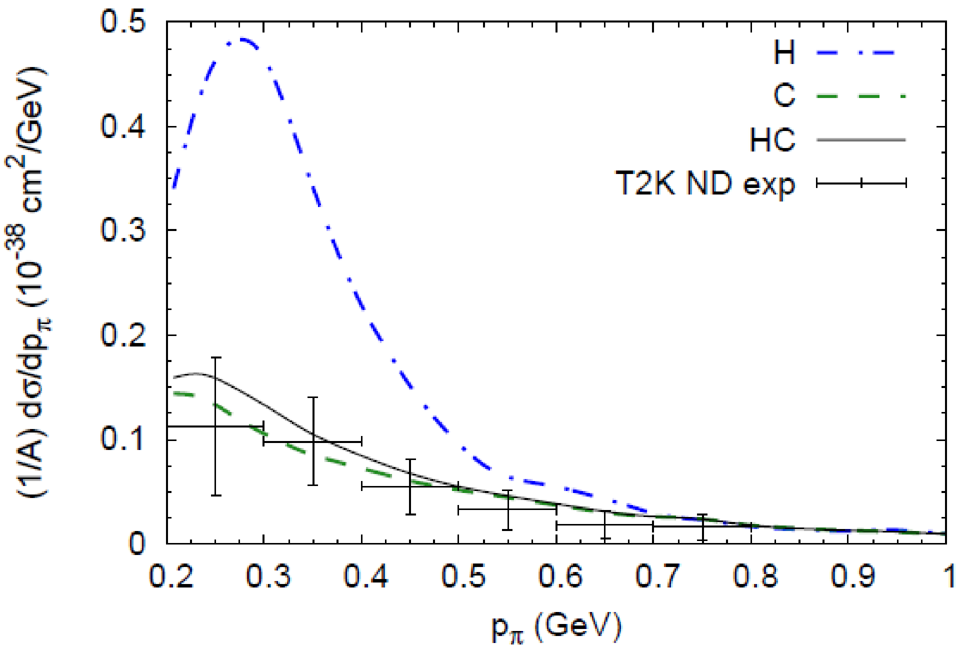
$CC\pi^0$ data: Aguilar-Arevalo, PRD83 (2011)



Comparison to T2K:

Mosel, Gallmeister, PRC99 (2019)

$CC\pi^\pm$ data: R. Castillo, PhD Thesis (2015)



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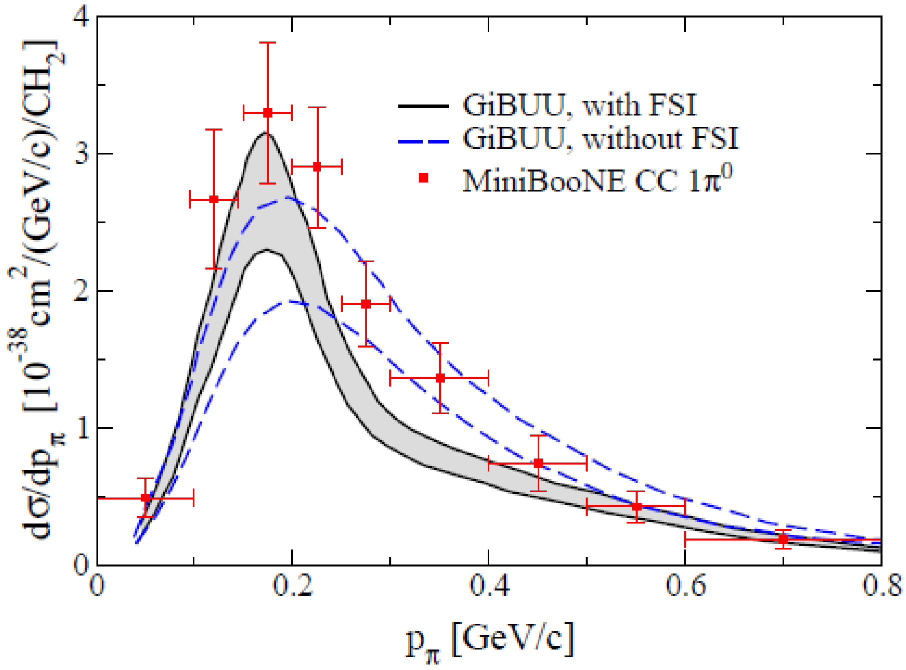
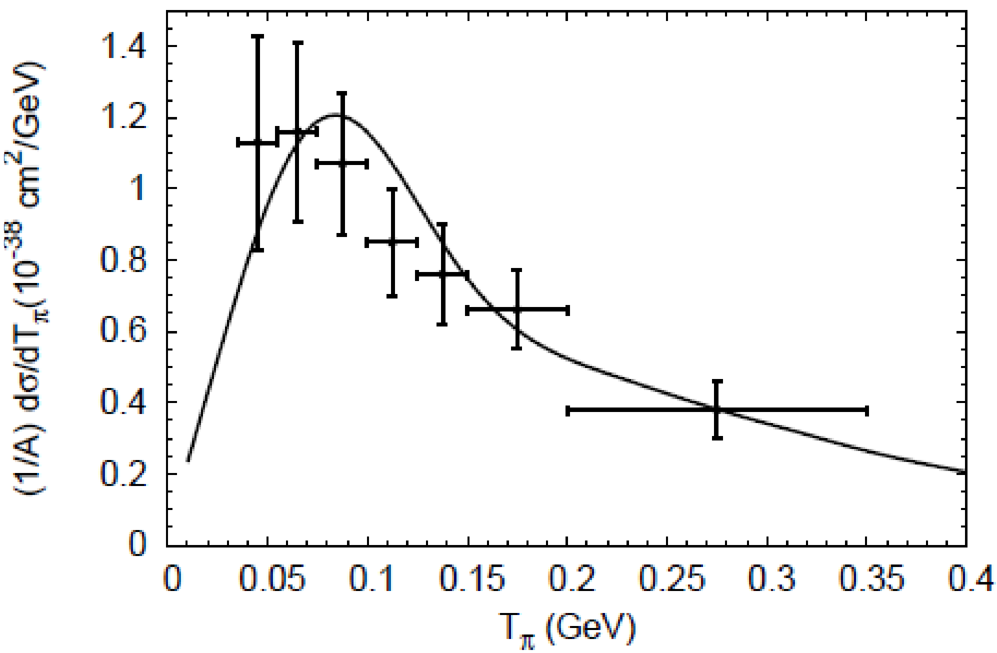


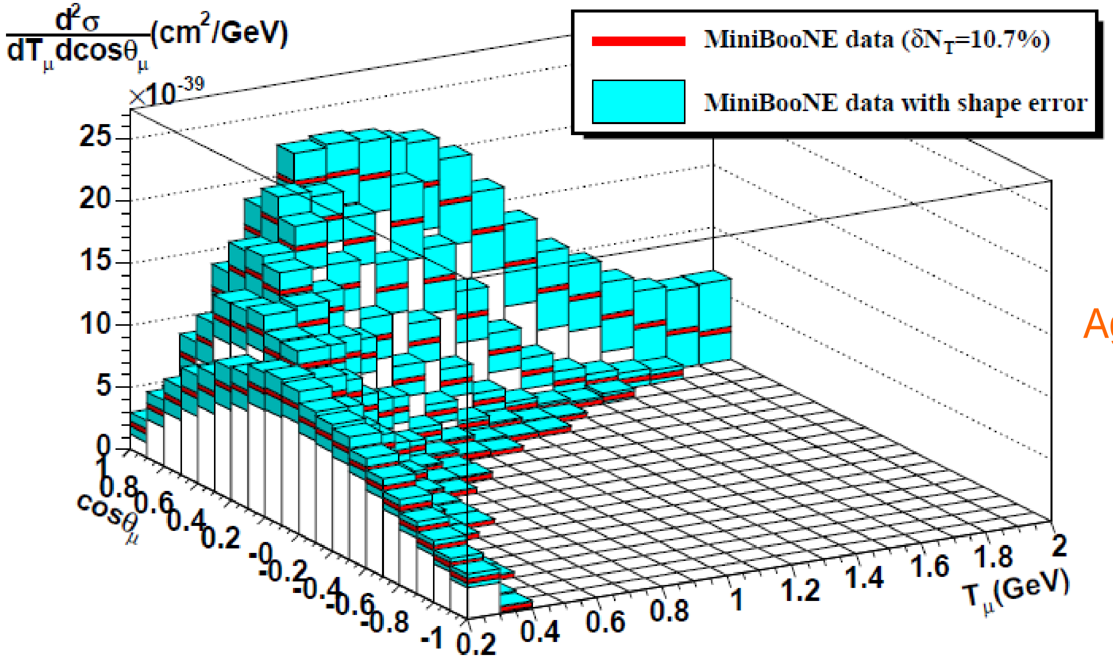
Comparison to MINERvA:
Mosel, Gallmeister, PRC96 (2017)
$CC\pi^\pm$ data: Eberly et al., PRD 92 (2015)



- In spite of flux difference, MiniBooNE and MINERvA data probe the same dynamics and should be strongly correlated Sobczyk, Zmuda, PRC 91 (2015)

Two-nucleon currents

- MiniBooNE data for "CCQE" 2D cross section:



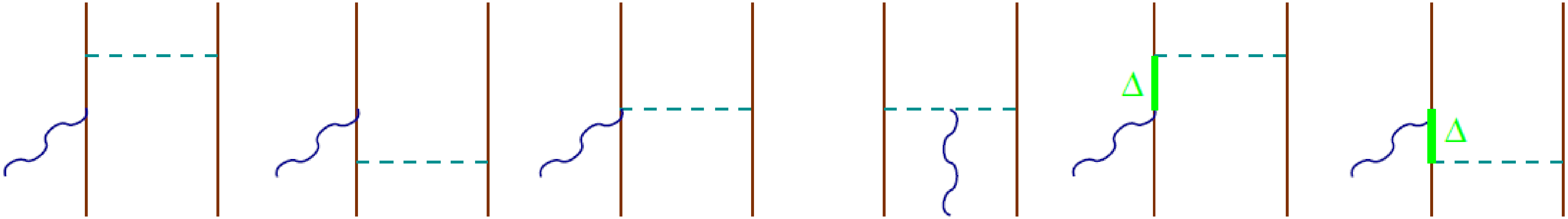
Aguilar-Arevalo et al., PRD81 (2010)

can be explained with a Relativistic Fermi Gas model and $M_A \approx 1.35$ GeV

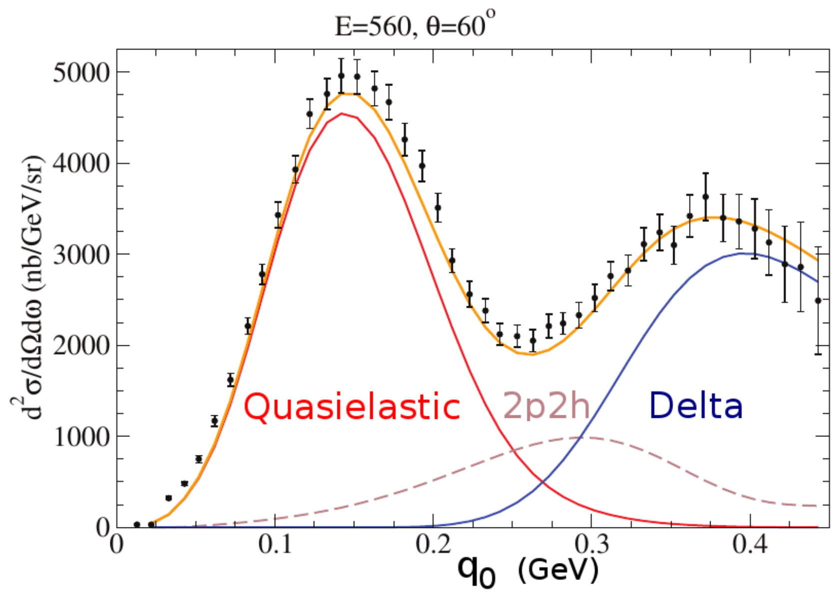
- in disagreement with $M_A \approx 1$ GeV from bubble chamber data
- but consistent with F_A from the z-expansion

Two-nucleon currents

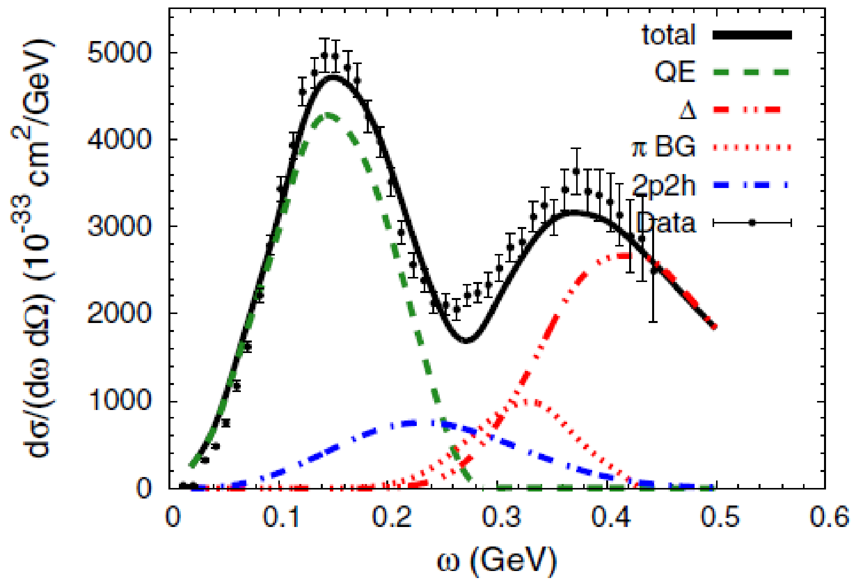
- 2-nucleon EW currents exist (are allowed by symmetries)



- Sizable contribution can be inferred from A(e,e')X



Megias et al., PRD 94 (2016)



Gallsmeiter et al., PRD 94 (2016)

Two-nucleon currents

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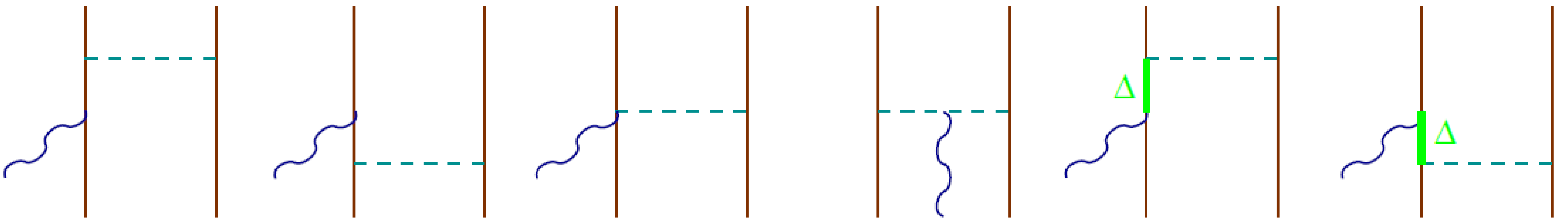
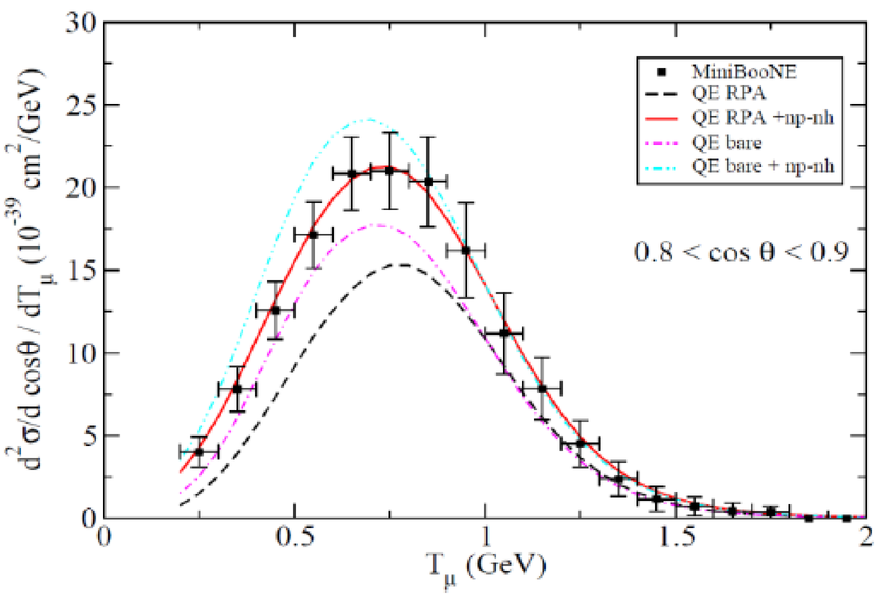
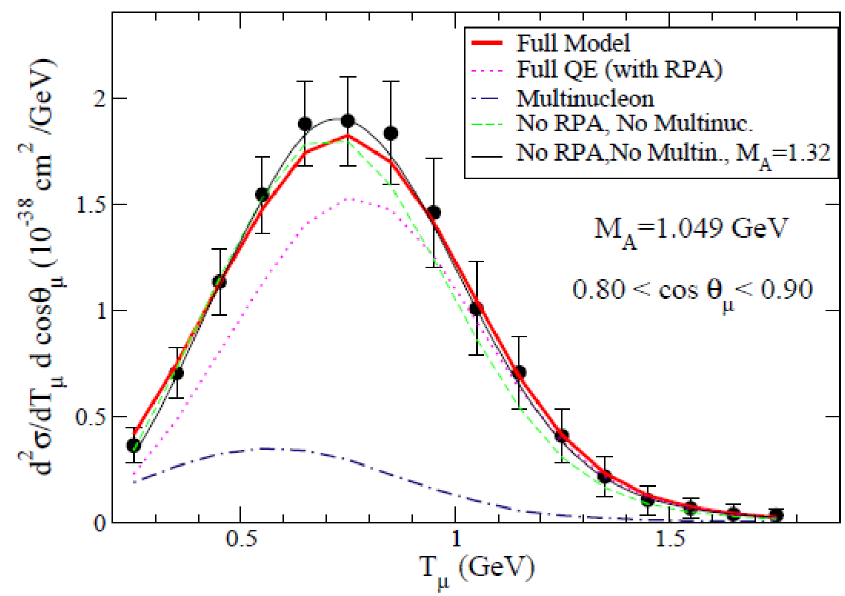


- together with better QE nuclear models can explain MiniBooNE data with $M_A \approx 1$ GeV



Martini et al.

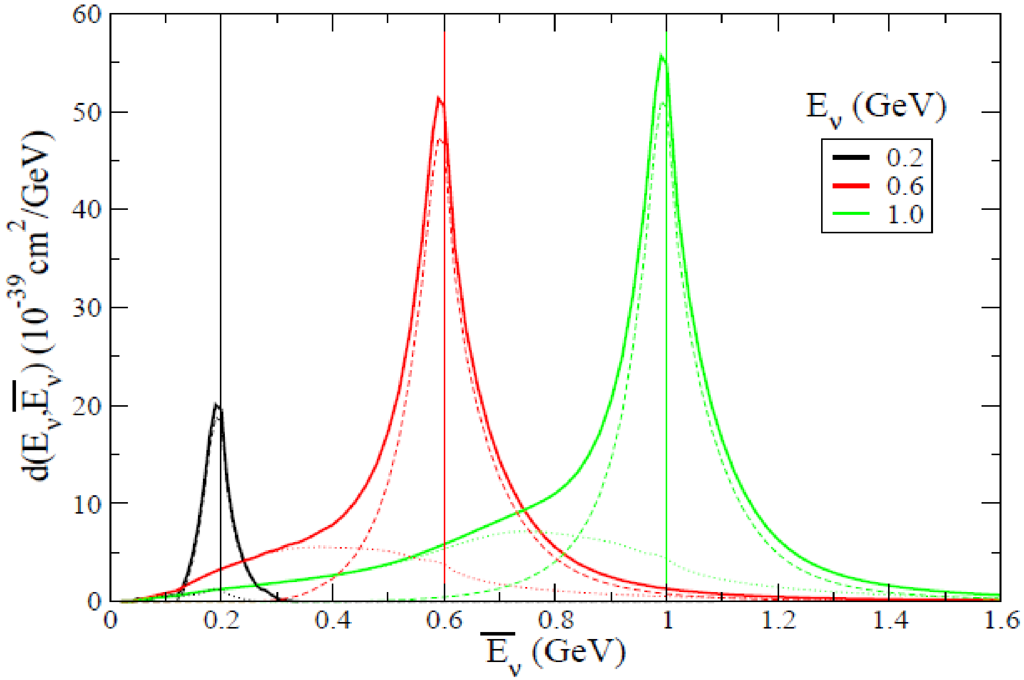


Nieves et al.

Two-nucleon currents

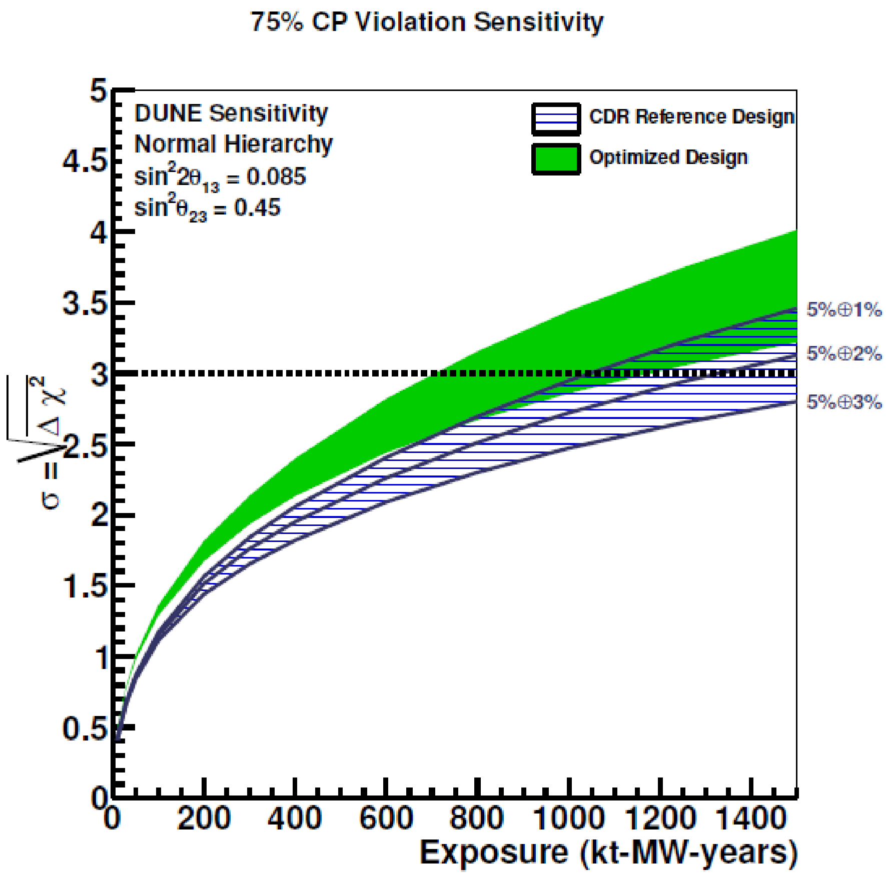
- Large implications for oscillation measurements
  - bias in (kinematic) E_ν reconstruction

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



Martini et al., PRD 87 (2013)

Conclusion



R. Acciarri et al., arXiv:1512.06148

" (...) the impact of pion and nucleon production through higher-energy inelastic interactions could play a key role. For instance, particles produced in nuclear interactions below detection threshold, or neutrons escaping detection, can lead to a large amount of missing energy. These effects are difficult to quantify as they rely on the predictions of a given nuclear model. Unless they are kept under control, they will generate a bias in the determination of neutrino energy towards lower energies, which in turn would translate into a wrong determination of the value of δ_{CP} ."

LAR et al., NuSTEC White Paper,
Prog. Part. Nucl. Phys. 100 (2018)

- Systematic errors are expensive: theory can help...