European Neutrino Town Meeting

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

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

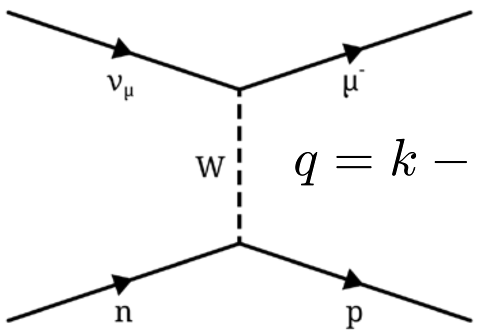
F. Sanchez @ NuPhys2015

- 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 $\approx$ 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-nucleus c.s. mismodeling could lead to unacceptably large systematic uncertainties or biased measurements
  Coloma, Huber, PRL 111 (2013)

Nucleon axial form factor

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

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



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

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

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

- 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, arXiv:1805.00905
- All methods obtain similar $F(Q^2)$...

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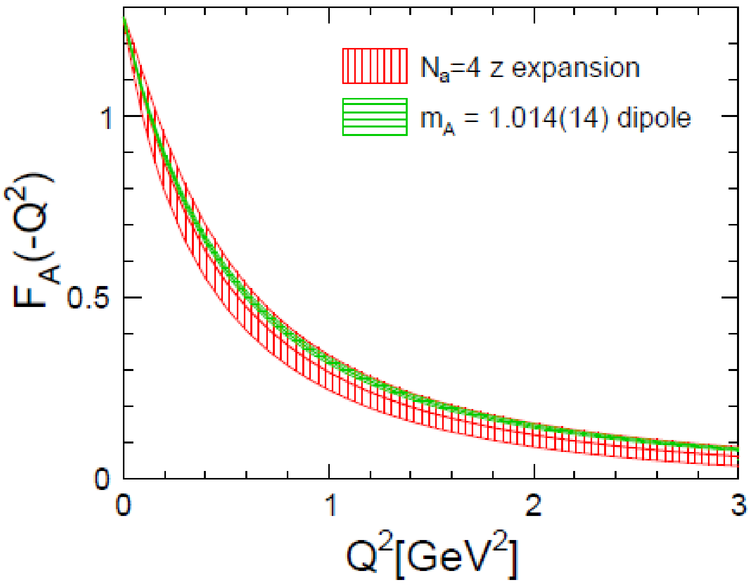
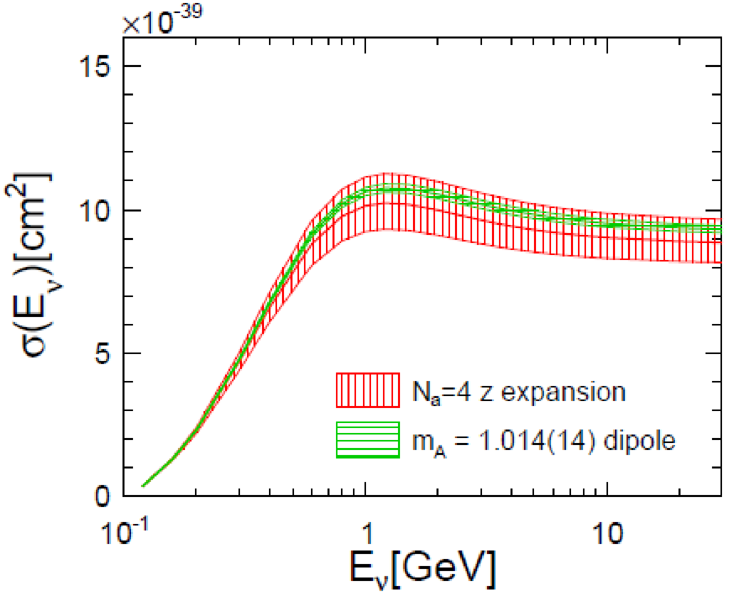
  - $\langle r_A^2 \rangle = 0.453(12)$ fm^2
- z-expansion: Meyer et al., PRD 93 (2016)
  - $\langle r_A^2 \rangle = 0.46(22)$ fm^2
- Neural networks + Bayesian statistics: LAR, Graczyk, Saúl-Sala, arXiv:1805.00905
  - $\langle r_A^2 \rangle = 0.471(15)$ fm^2 $\leftarrow$ ANL only so far
- All methods obtain similar $F(Q^2)$...
- ... but with different errors

QE scattering on the nucleon

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

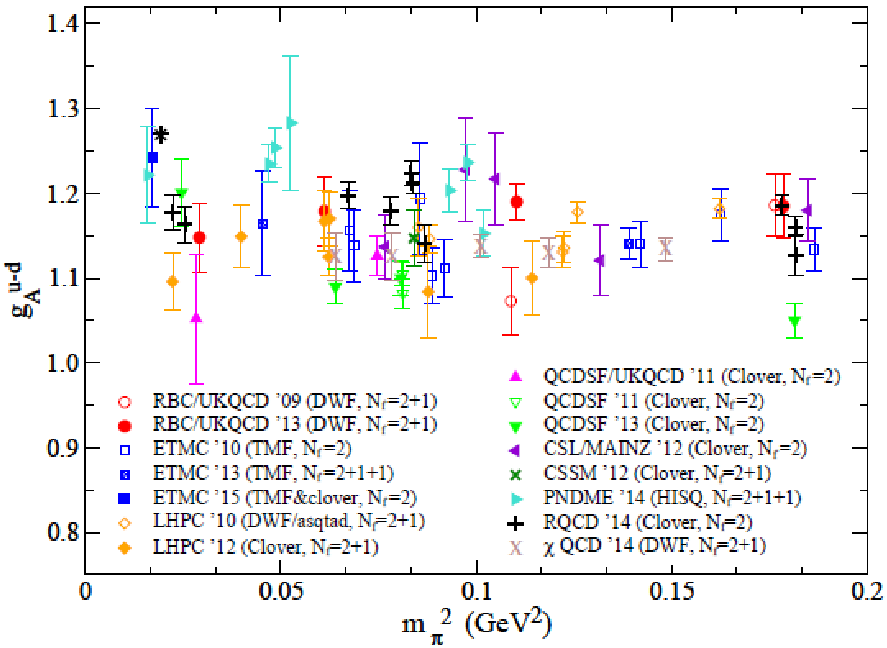




- At $E_\nu \sim 1$ GeV σ(CCQE) has $\approx$ 10 % error
- More precise information about F_A is needed
  - Direct or indirect CCQE measurement on n/p
  - Lattice QCD

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
  - A per-cent-level determination of the nucleon axial coupling from QCD

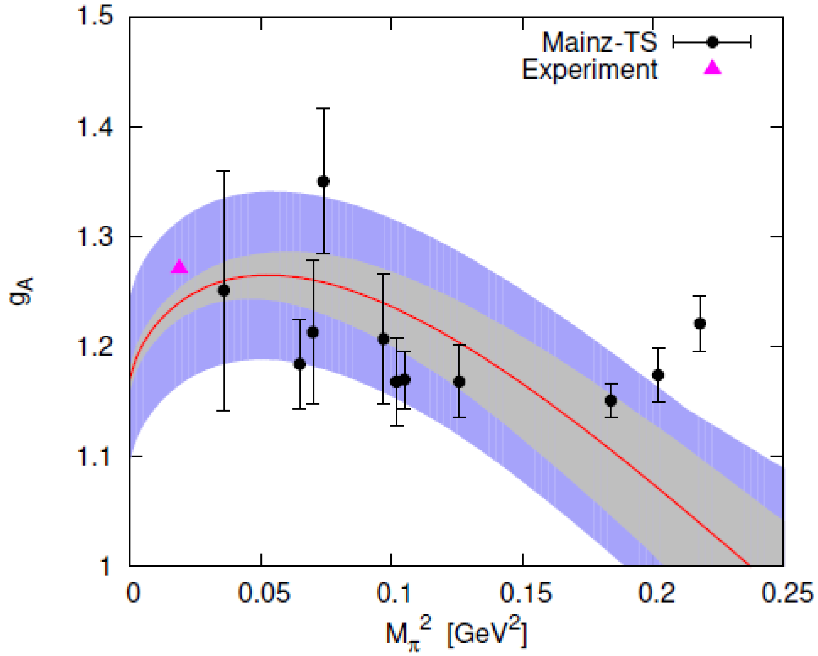
Chang et al., Nature 558 (2018)

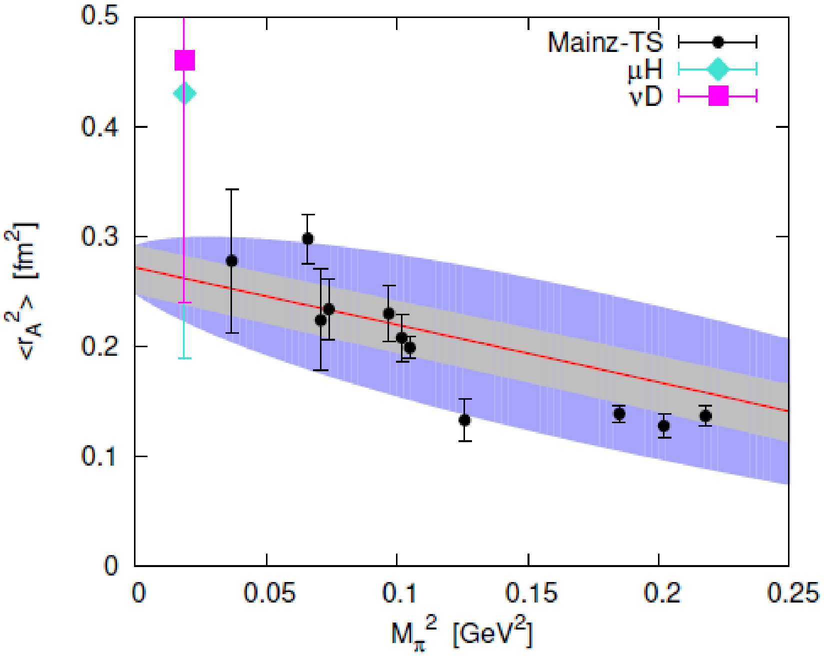
F_A & LQCD

- 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 $\Delta(1232)$





  - $g_A = 1.237(74)$, $\langle r_A^2 \rangle = 0.263(38)$ fm^2

1π production on the nucleon

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

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

1π production on the nucleon

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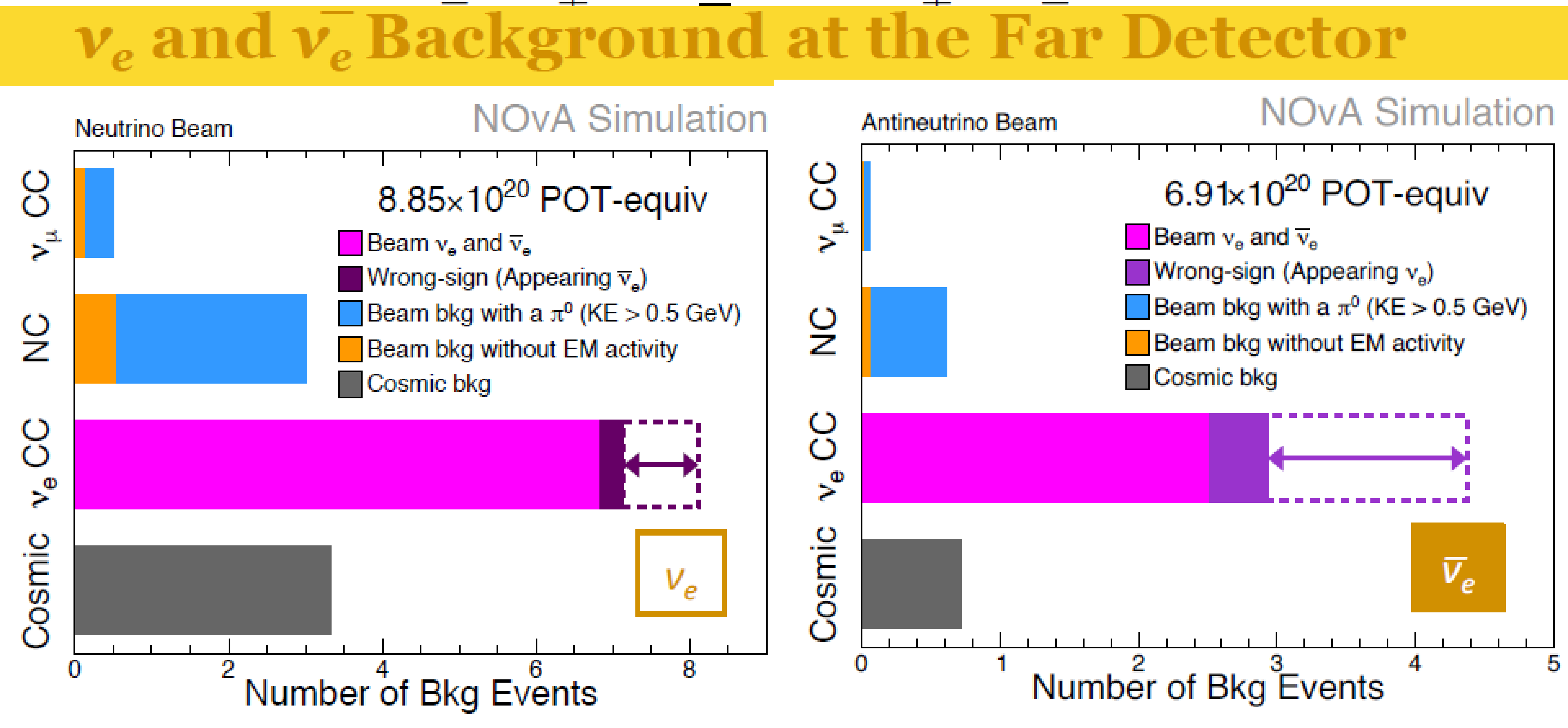


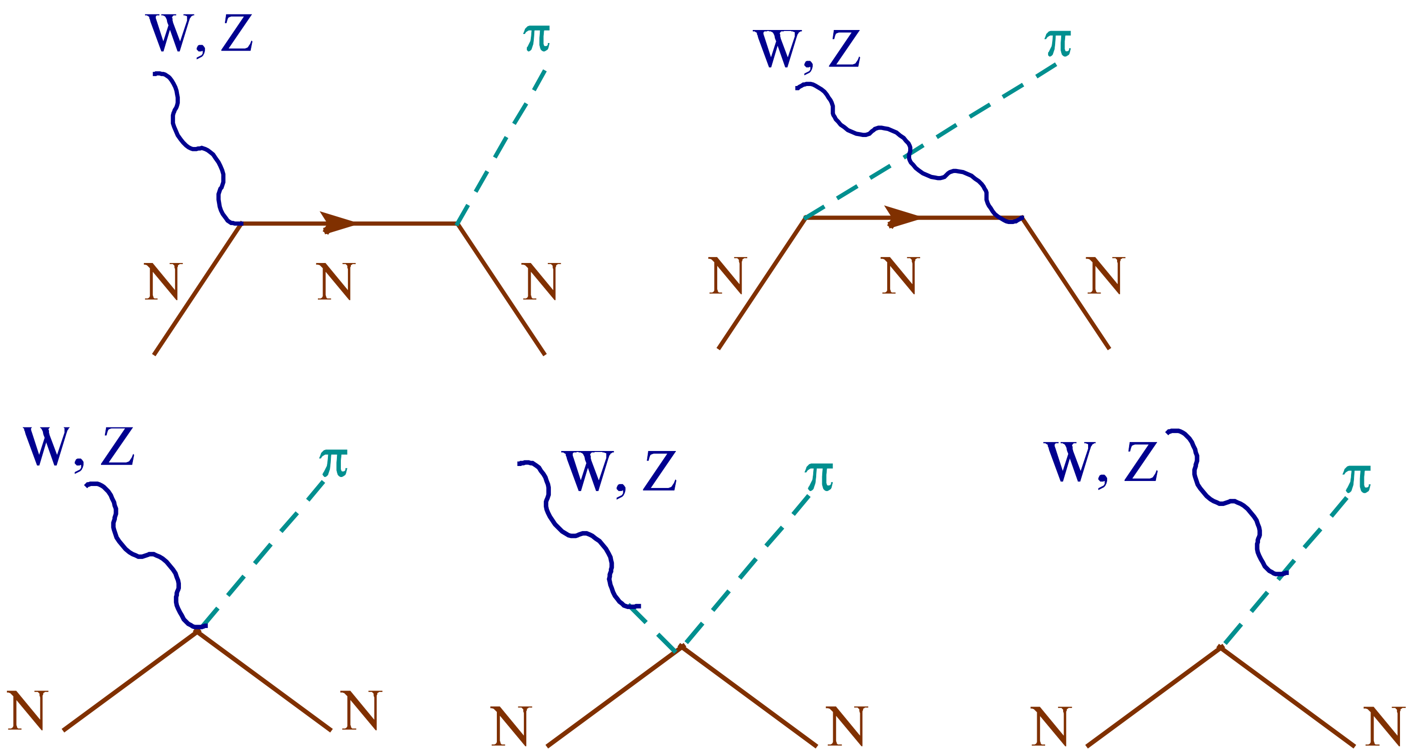
M. Muether @ NUSTEC 2018

- e-like background to $\nu_\mu \rightarrow \nu_e$ (T2K, NOvA)

1π production on the nucleon

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

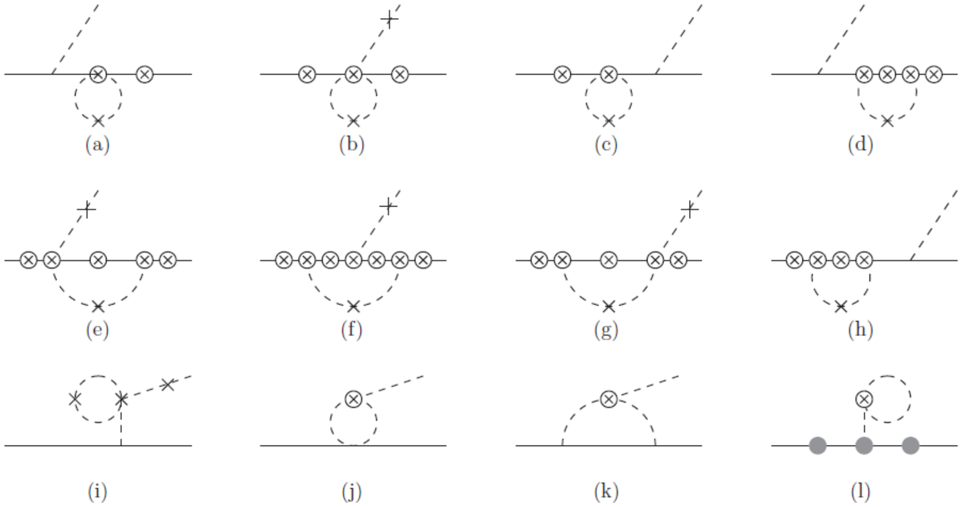
- From Chiral symmetry:



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

Weak pion production in ChPT

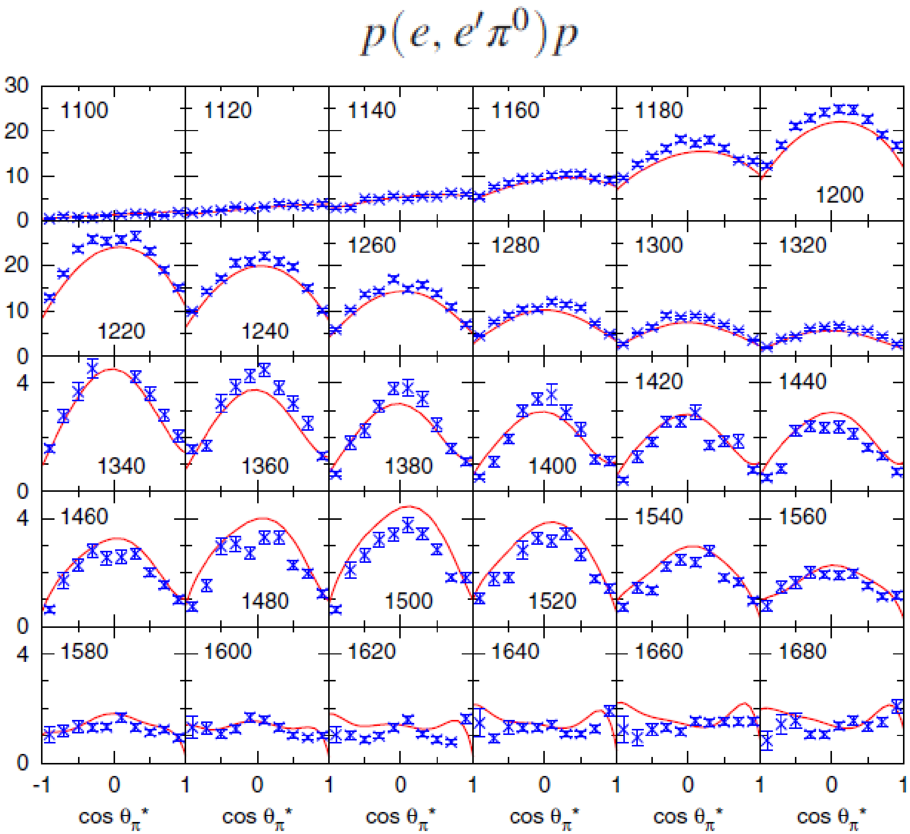
- First study in ChPT: Yao et al., PRD 98 (2018)
- Part of a comprehensive study of
  $\pi N \to N\pi$, $\gamma^* N \to N \pi$, $W^*, Z^* N \to N \pi$, ...
- EOMS, explicit $\Delta(1232)$, O(p^3) in the δ-counting: $\delta = m_\Delta - m_N \sim O(p^{1/2})$

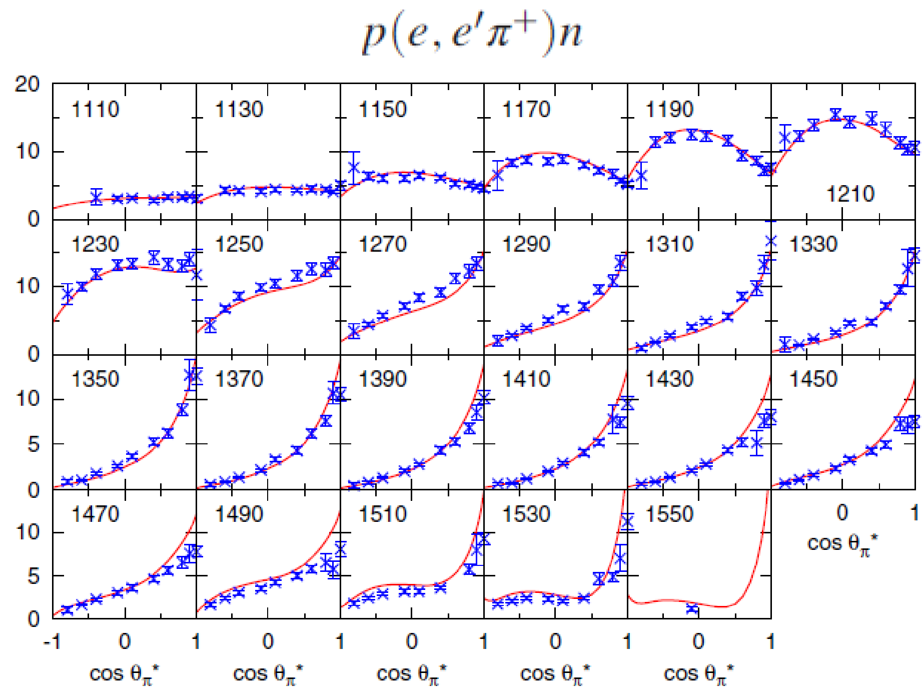


- LECs : 22 in total
  - 7 unknown (not very relevant)
    - 4 can be extracted from pion electroproduction
    - information about remaining 3 could be obtained from new close-to-threshold measurements of ν-induced π production on protons
- Valid only close to threshold
- Benchmark for phenomenological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

- Pheno models rely on (non-ν) data as input and/or validation
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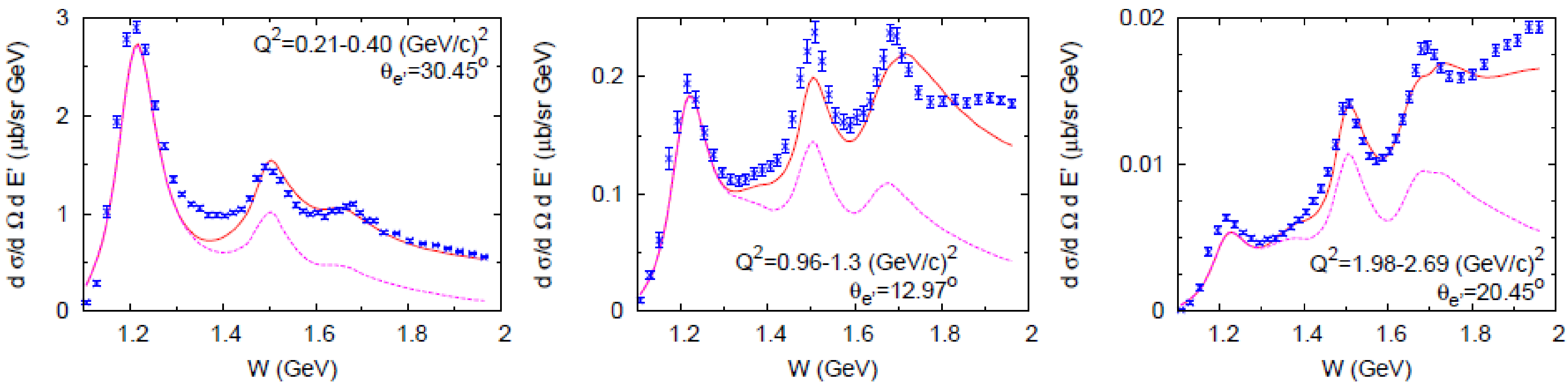
  - Axial current at $q^2 \to 0$ can be constrained with $\pi N \to N\pi$ (PCAC)

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



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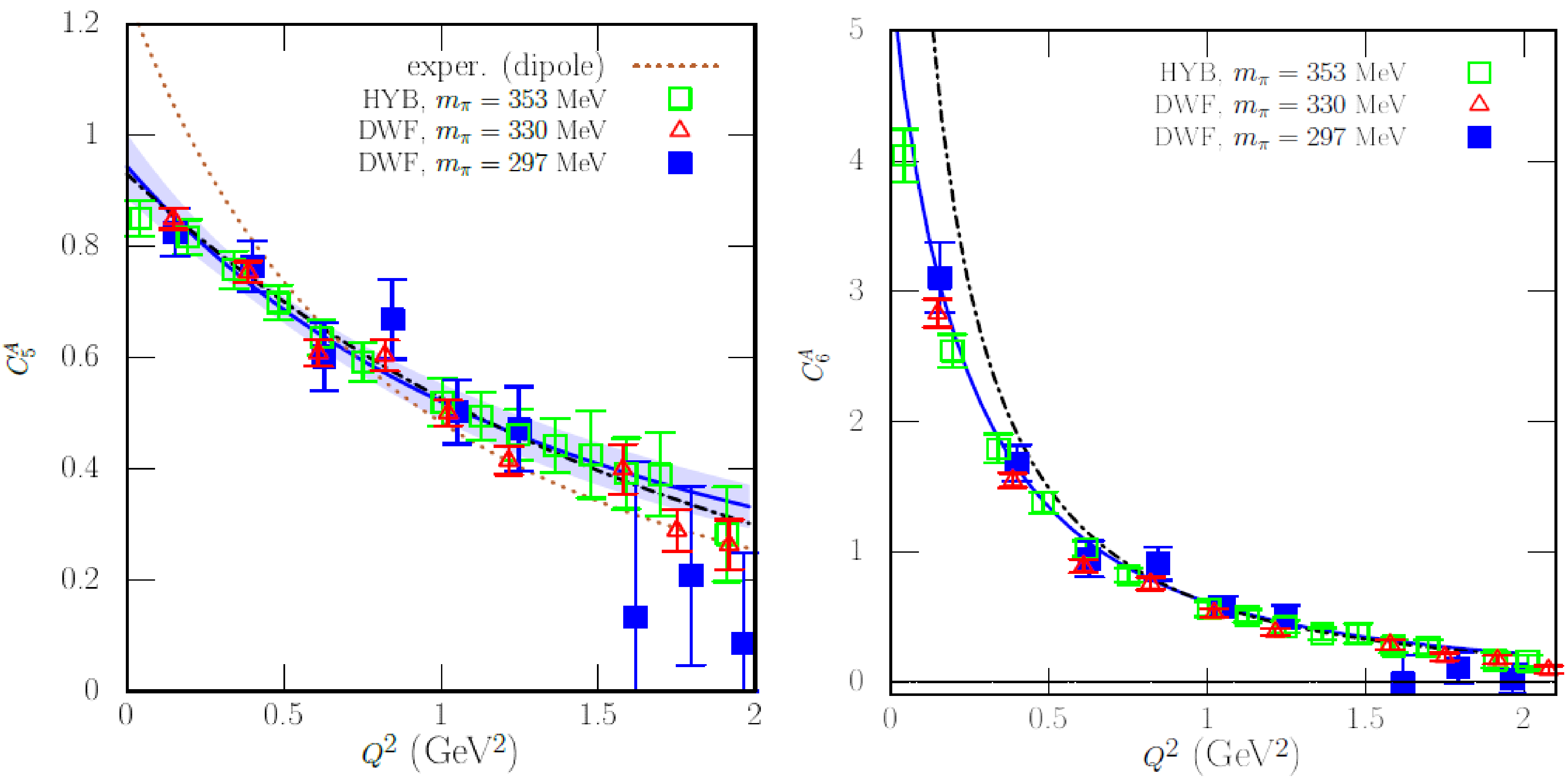
  - Very limited information about the axial current at $q^2 \neq 0$
    - Some on N-Δ(1232) from ANL and BNL data on $\nu_\mu d \to \mu^- \pi^+ p n$
    - Direct or indirect CCQE measurement on n/p
    - Lattice QCD

Inelastic form factors & LQCD

- N-Δ axial form factors in LQCD

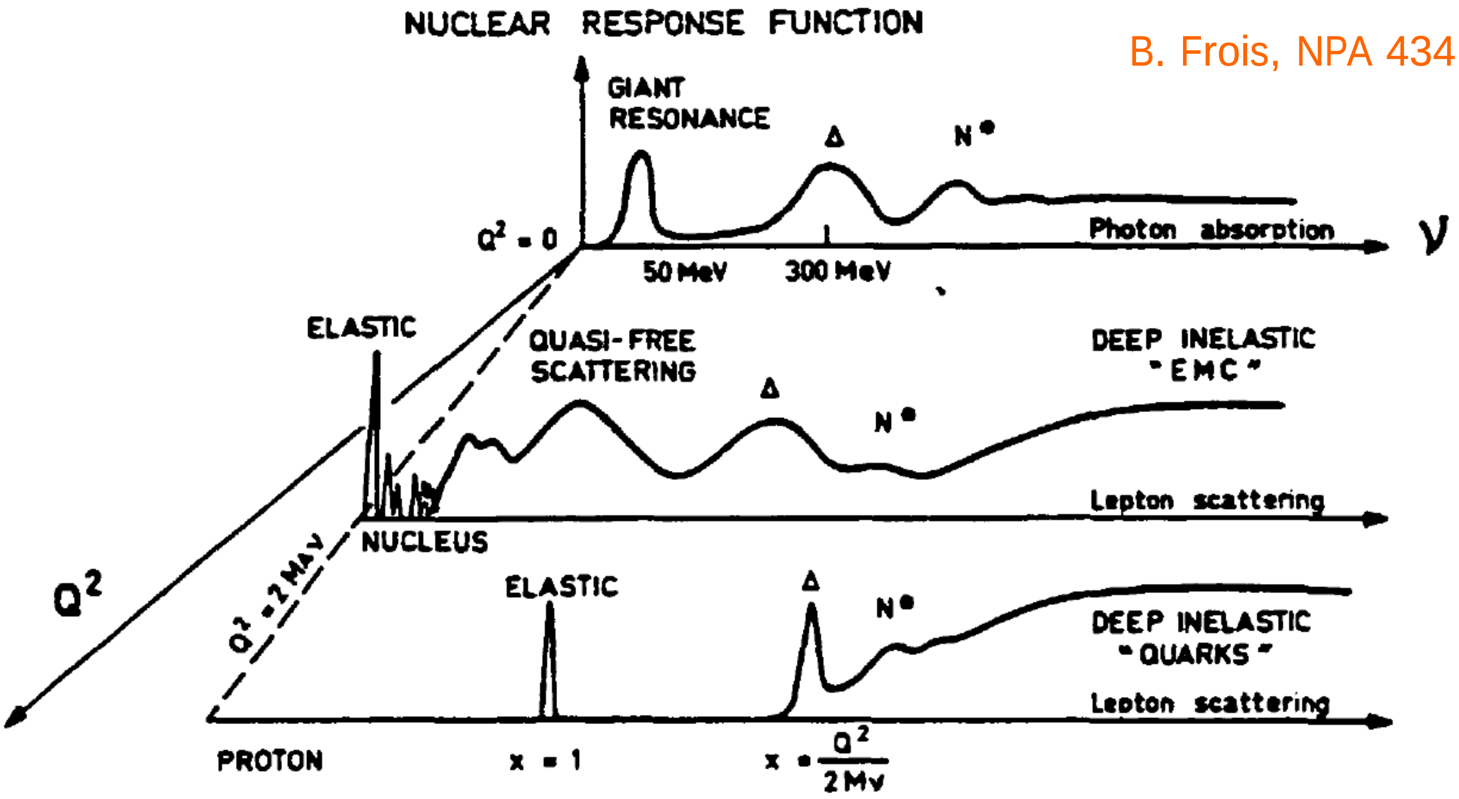
  Alexandrou et al., PRD83 (2011)



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, ...

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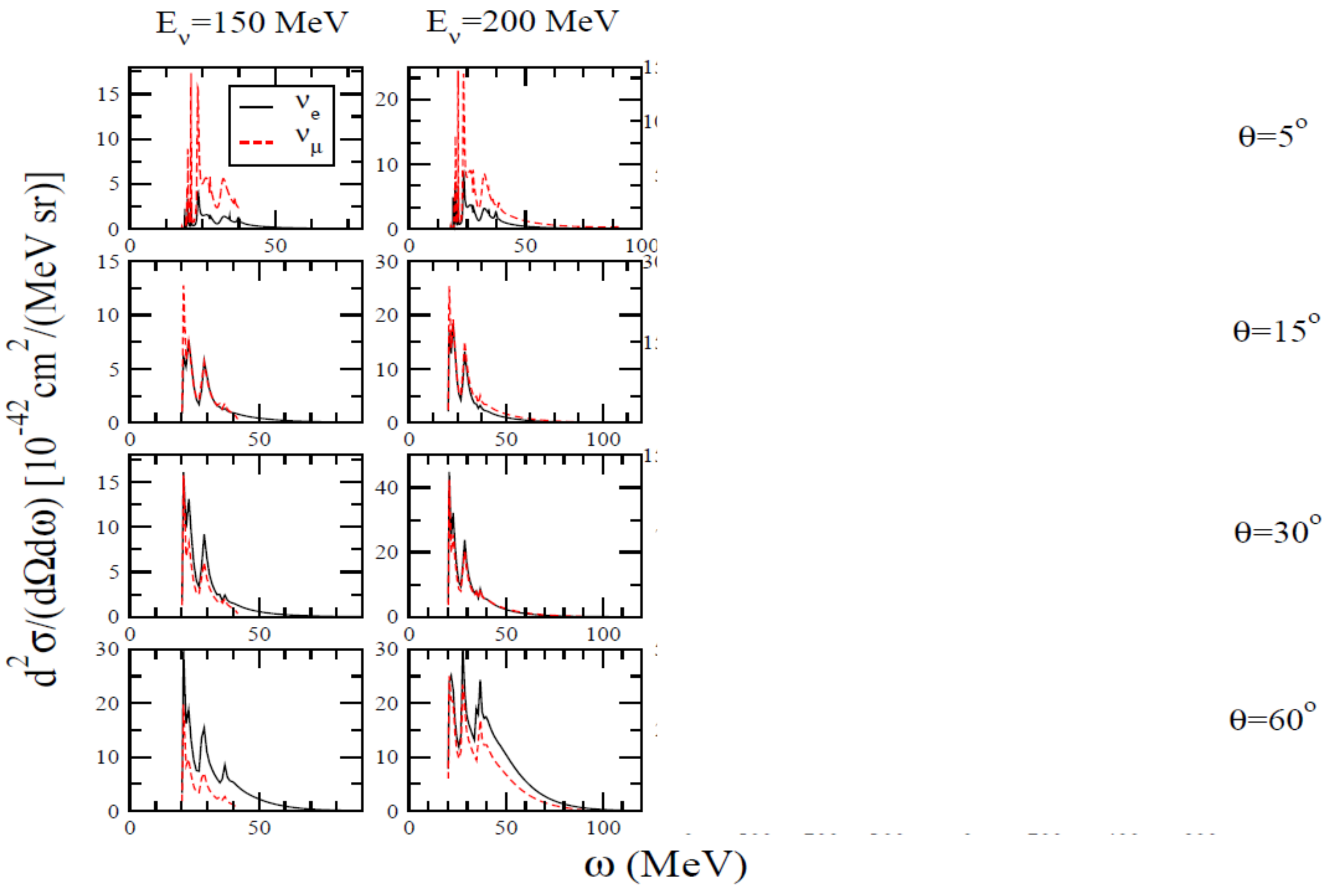
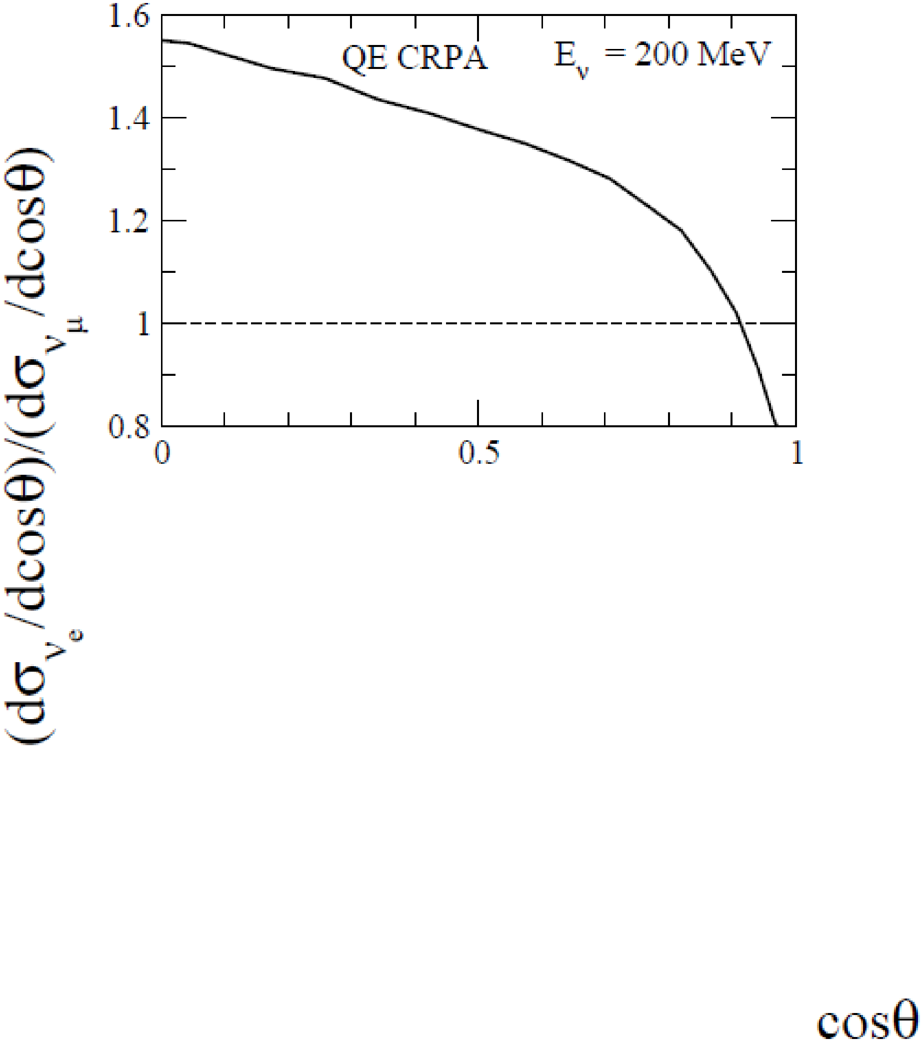


CRPA Gent, Jachowicz et al.

$\sigma(\nu_e)/\sigma(\nu_\mu)$



Martini, Jachowicz et al., PRC94 (2016)

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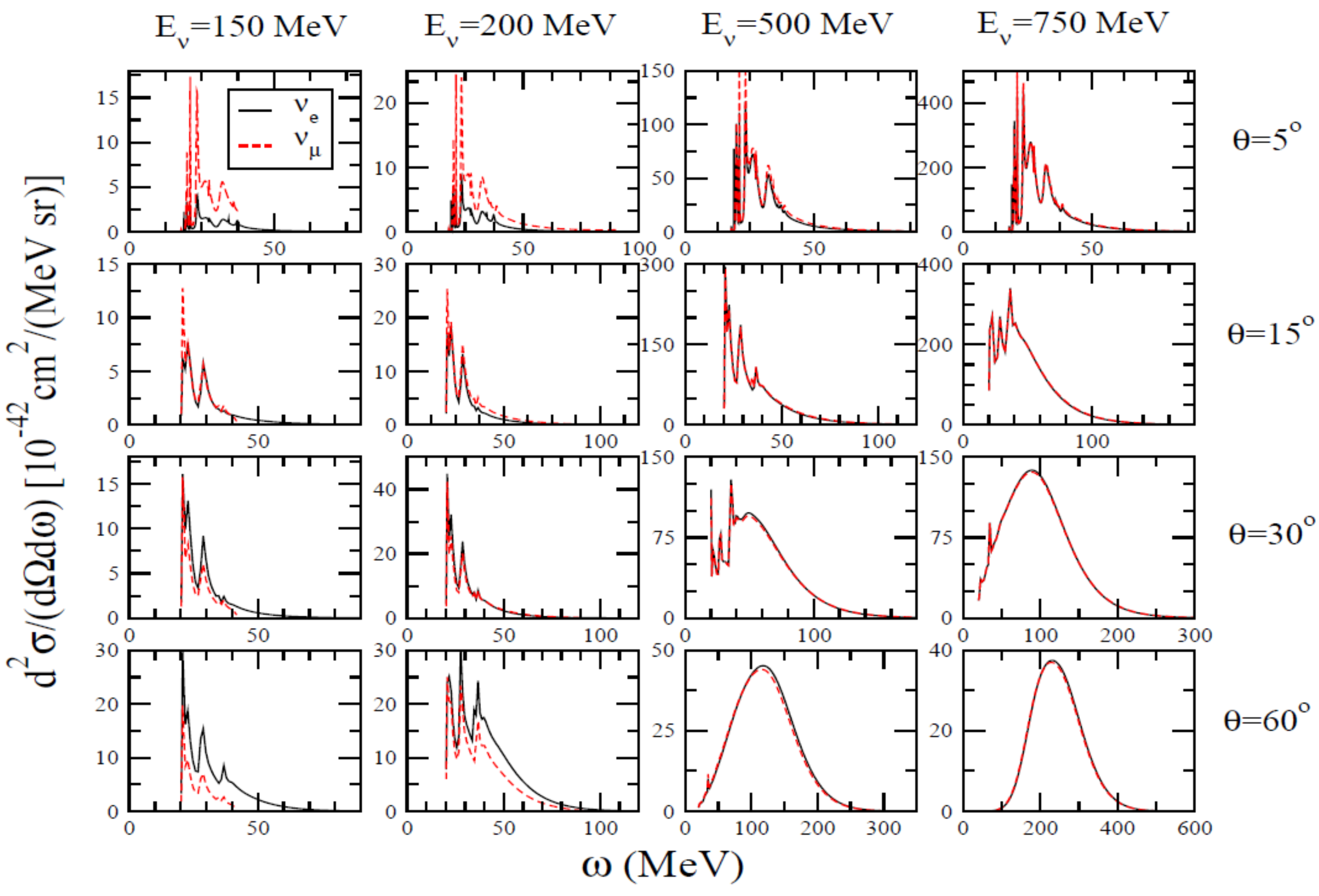

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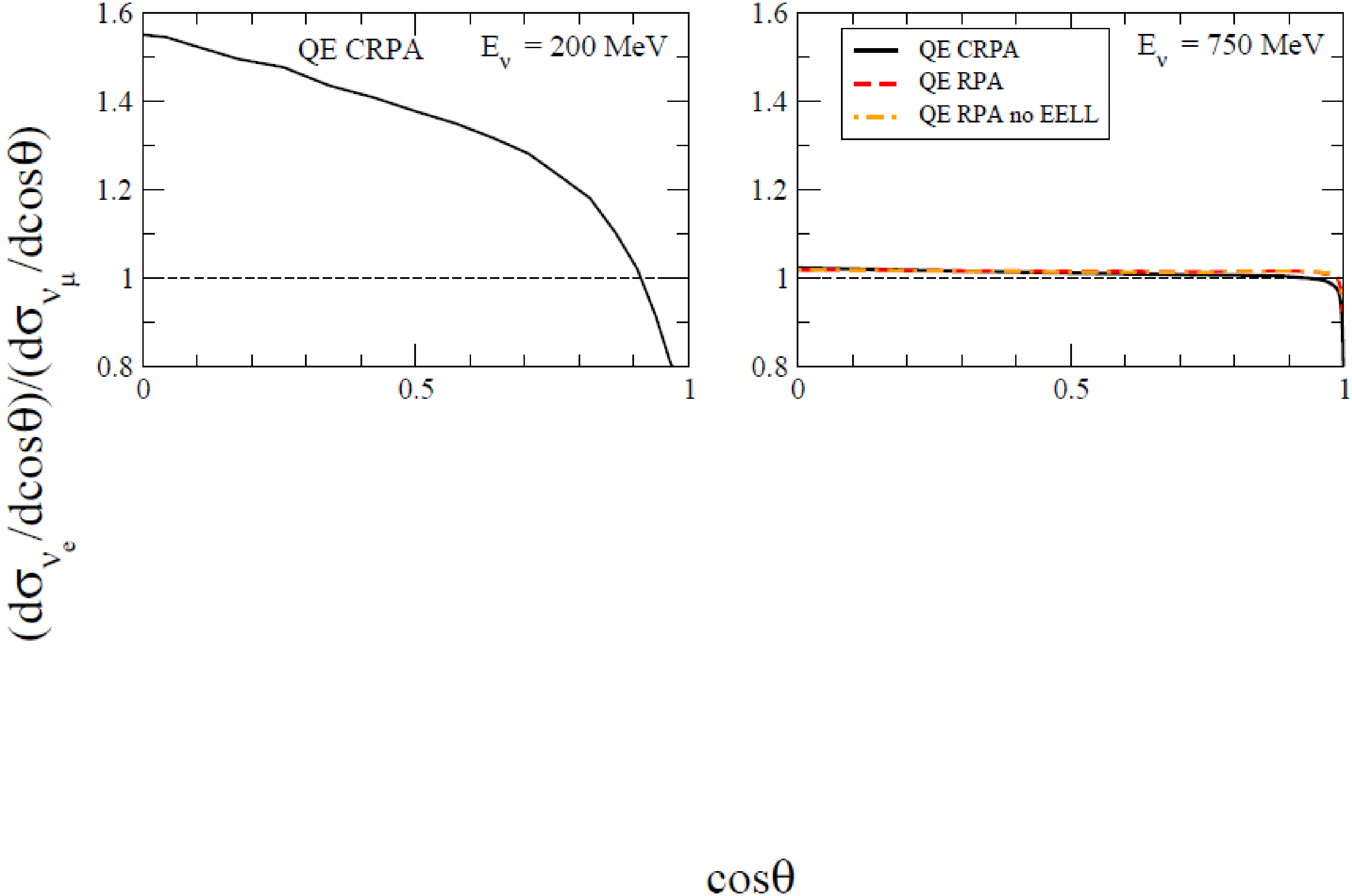

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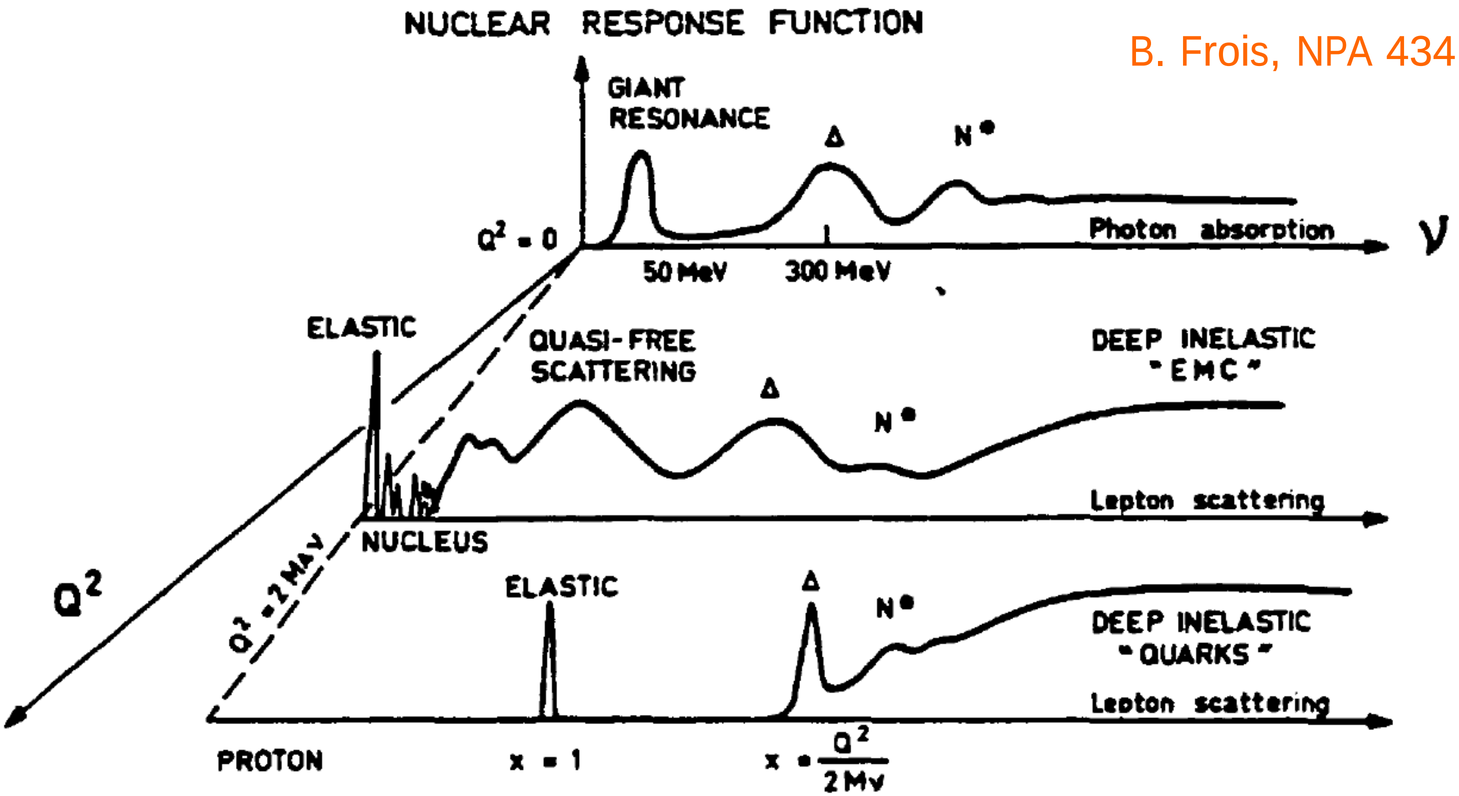

- Shell structure, collective excitations, QE peak, ...
- initial state description: non-relativistic)
- final state interactions: (relativistic) NN, πN, ...

Neutrino interactions on nuclei

- Impulse approximation: interactions on single nucleons in the presence of mean fields and short-range correlations
  - Spectral functions:

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

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

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

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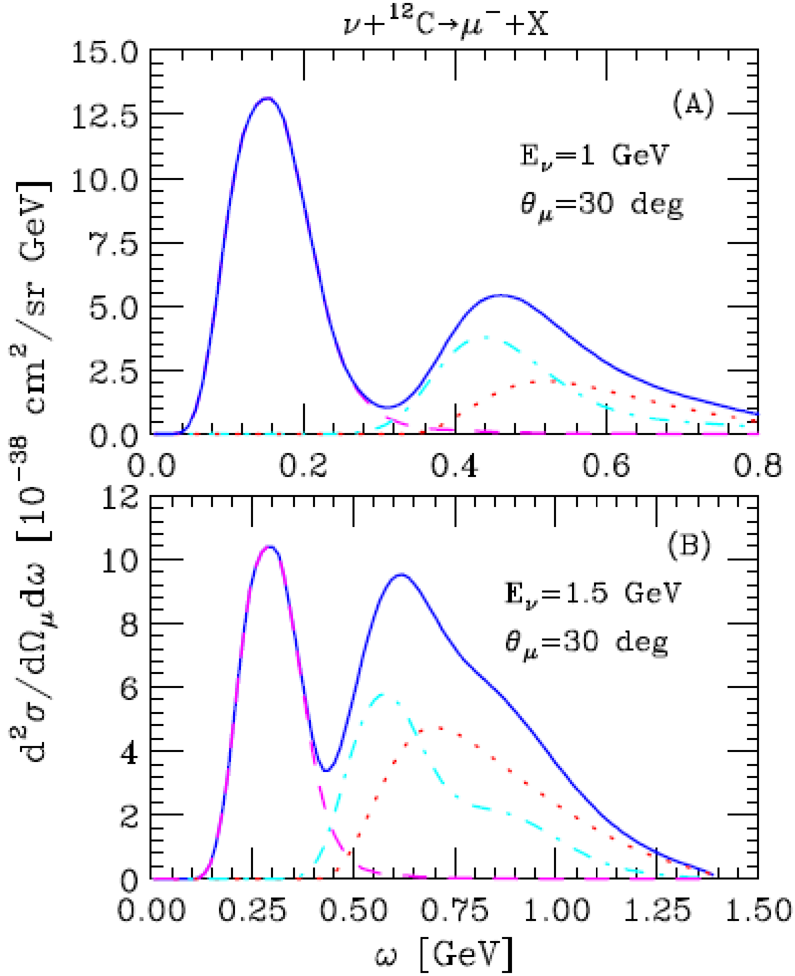
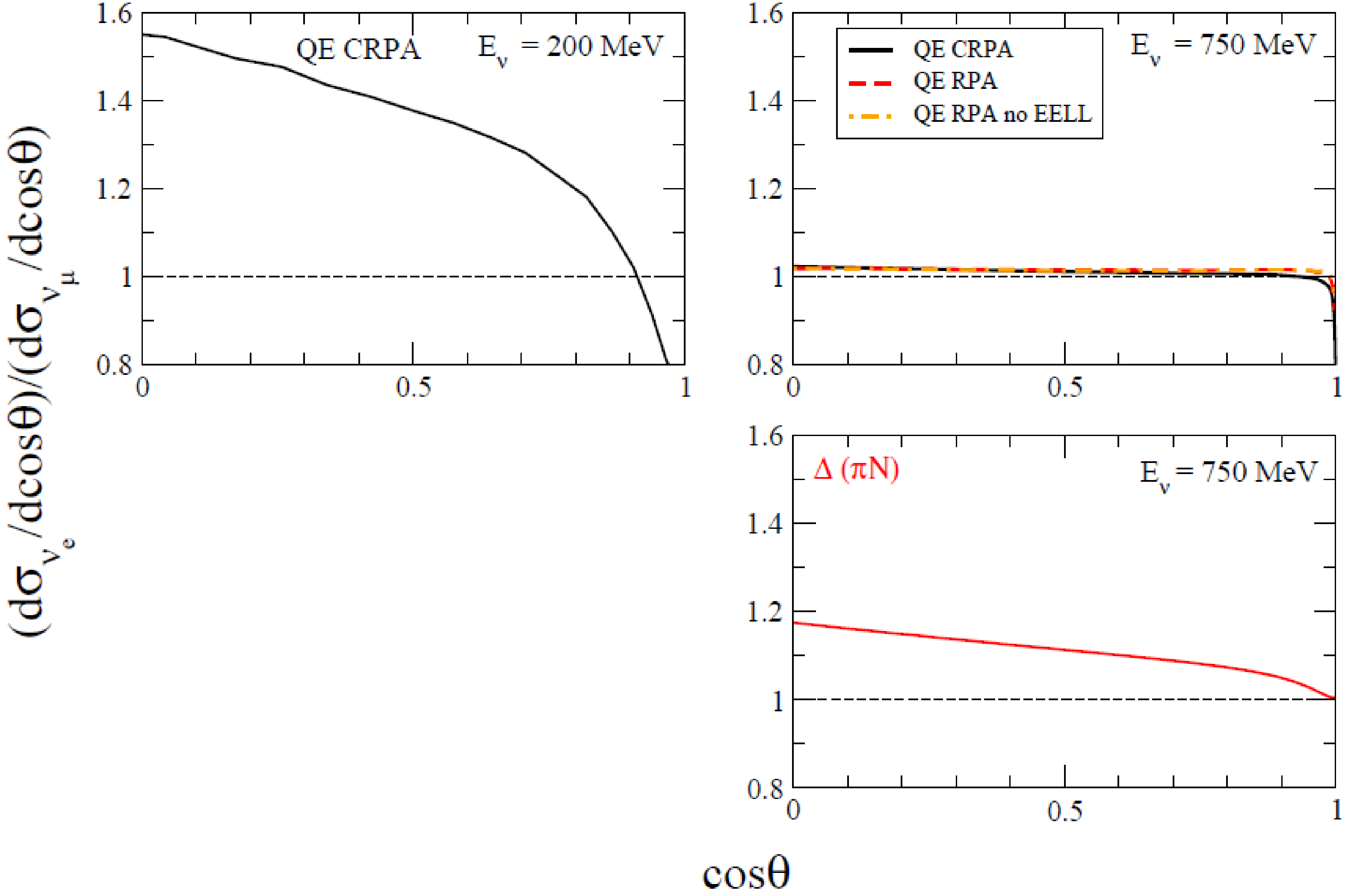
$$\mathcal{A}_{p,h}(p) = \mp\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(p)}{[p^2 - M^2 - \mathrm{Re}\Sigma(p)]^2 + [\mathrm{Im}}$$

  - Inclusive cross section in the QE and inelastic regions:



Vagnoni, Benhar, Meloni, PRL 118 (2017)

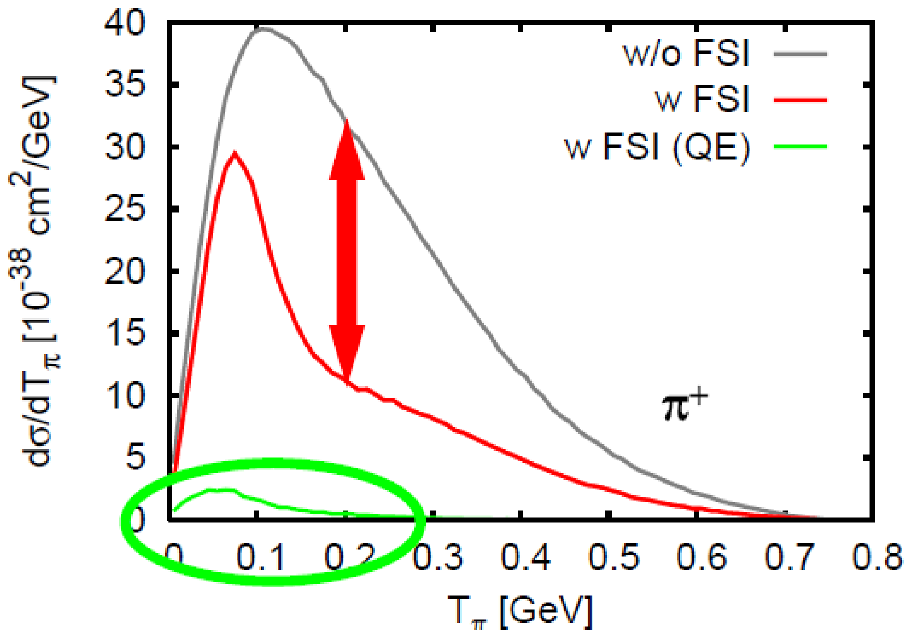
$\sigma(\nu_e)/\sigma(\nu_\mu)$

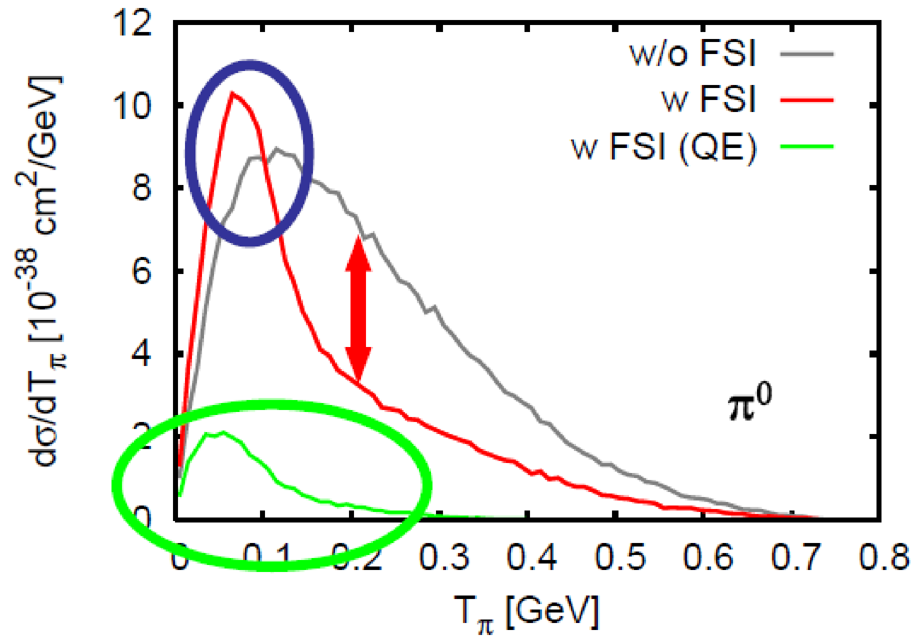


Martini, Jachowicz et al., PRC94 (2016)

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

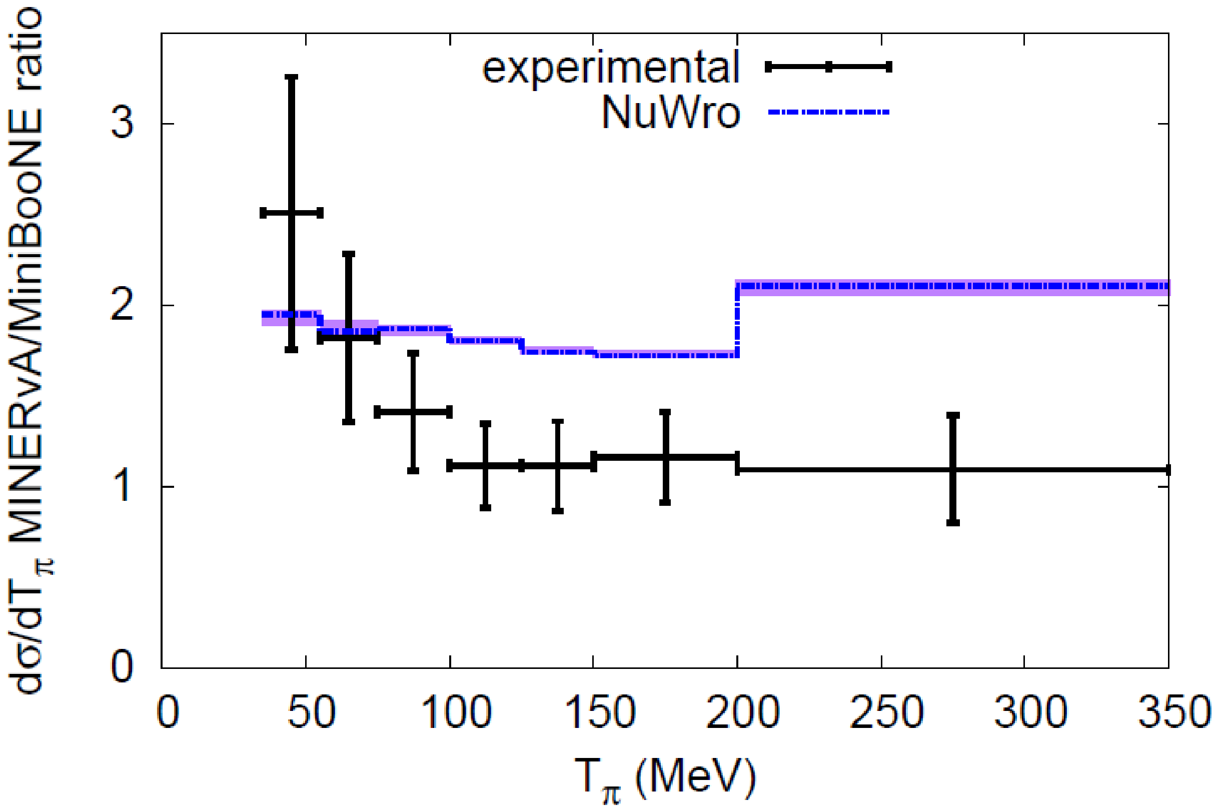




$$\nu_\mu + {}^{56}Fe \rightarrow \mu^- \, \pi \, X \quad E_\nu = 1 \text{ GeV}$$

1π production on nuclei

- Experimentally studied by MiniBooNE, T2K (ND280) and MINERvA

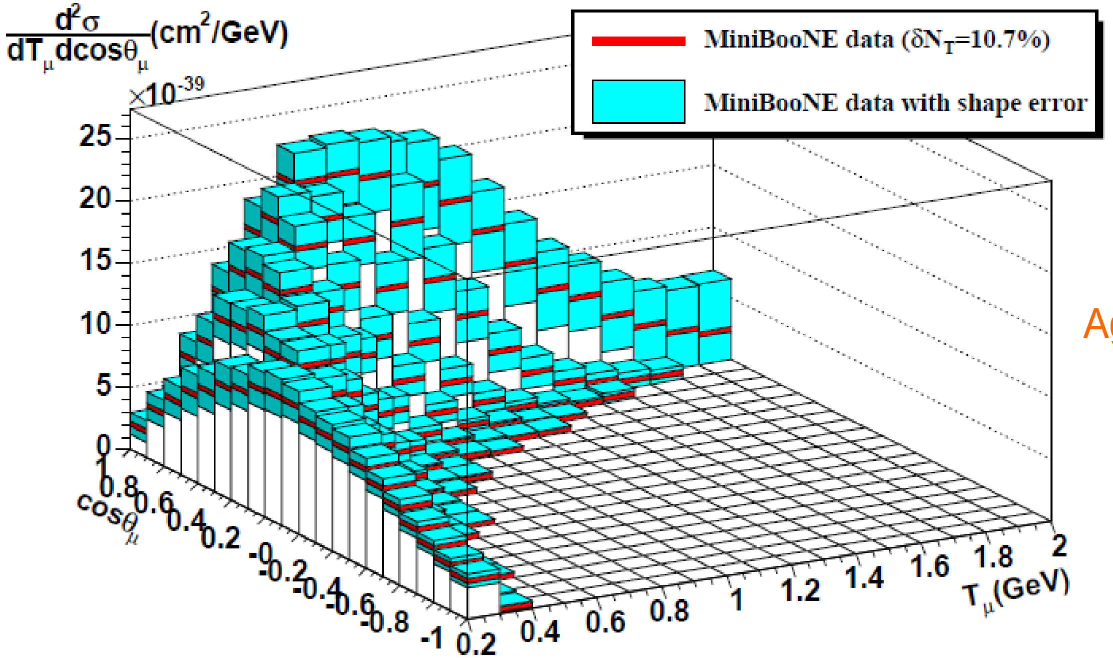


Sobczyk, Zmuda, PRC 91 (2015)

- In spite of flux difference, MiniBooNE and MINERvA data probe the same dynamics and should be strongly correlated

Two-nucleon currents

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



Aguilar-Arevalo et al., PRD81 (2010)

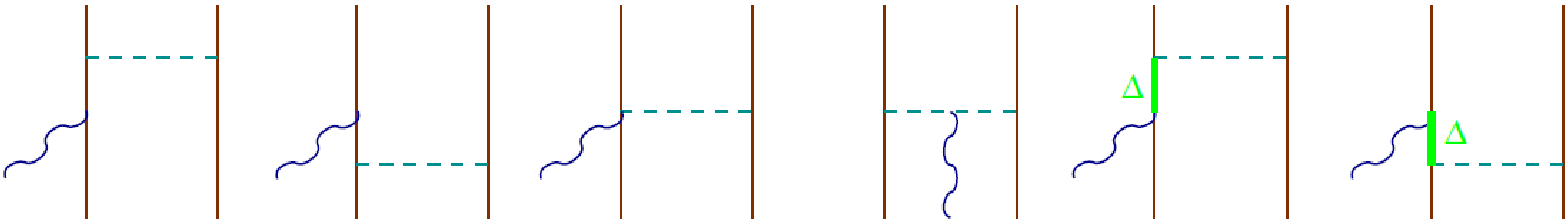
can be explained with a Relativistic Fermi Gas model and $M_A \approx 1.35$ GeV

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

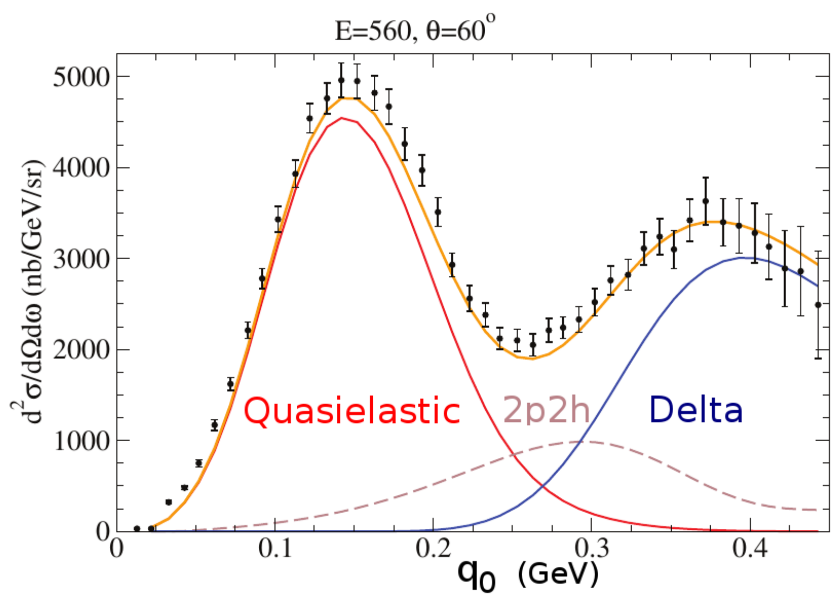
$$F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

Two-nucleon currents

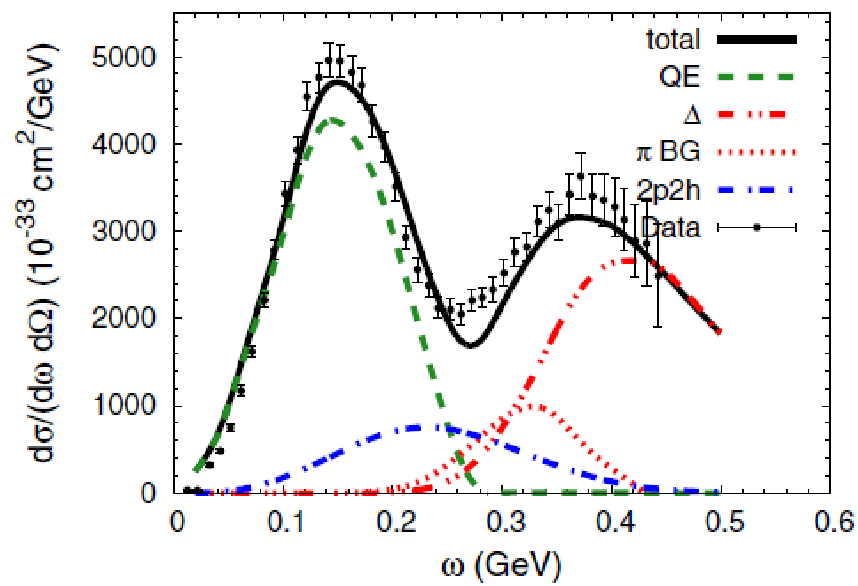
- 2-nucleon EW currents exist (are allowed by symmetries)



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



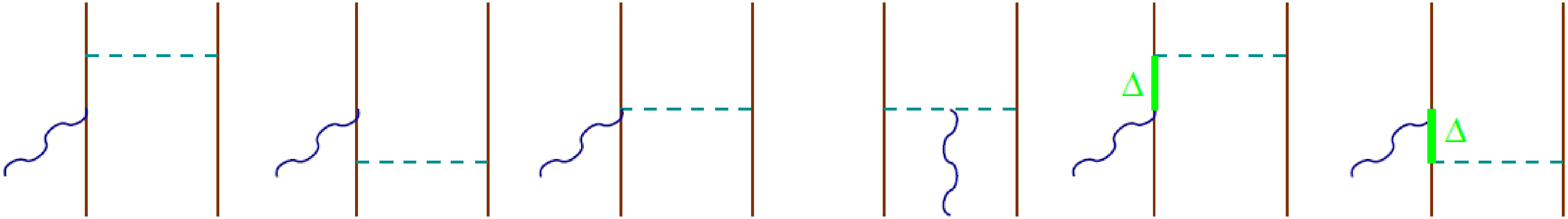
Megias et al., PRD 94 (2016)



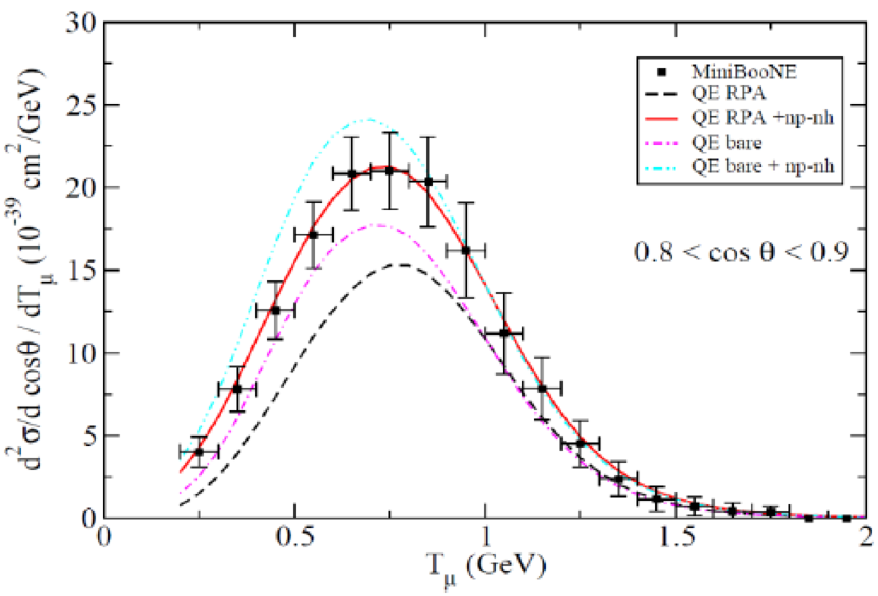
Gallsmeiter et al., PRD 94 (2016)

Two-nucleon currents

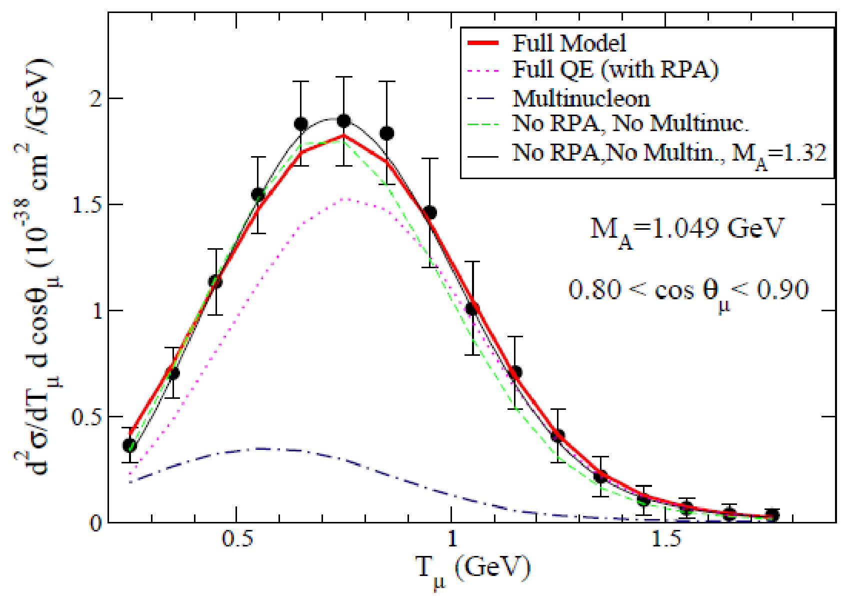
- 2-nucleon EW currents exist (are allowed by symmetries)



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



Martini et al.

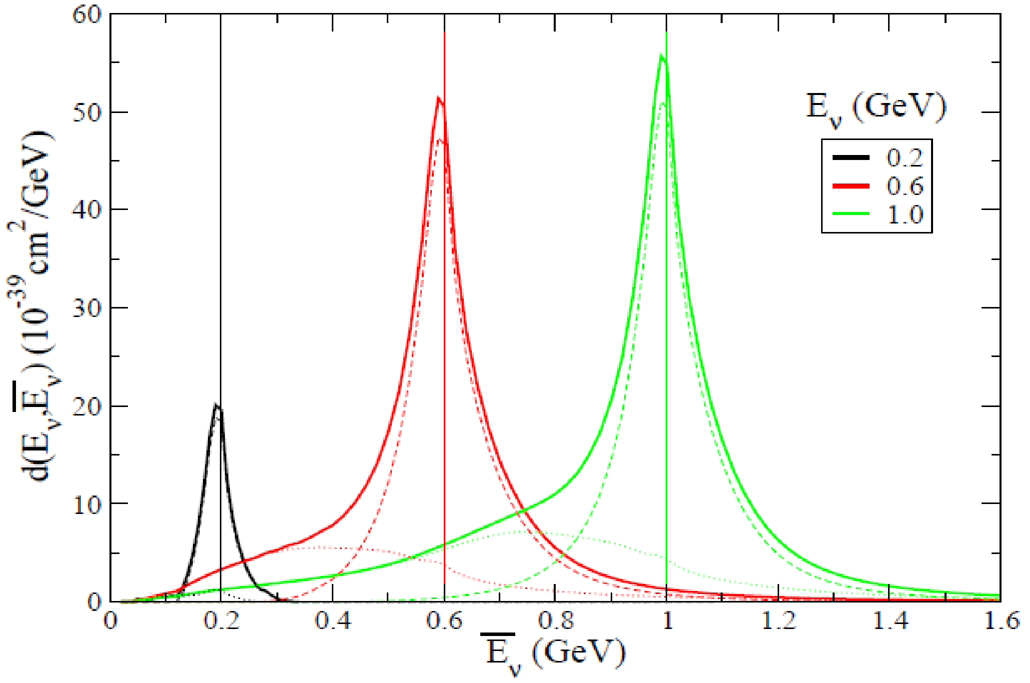


Nieves et al.

Two-nucleon currents

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

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

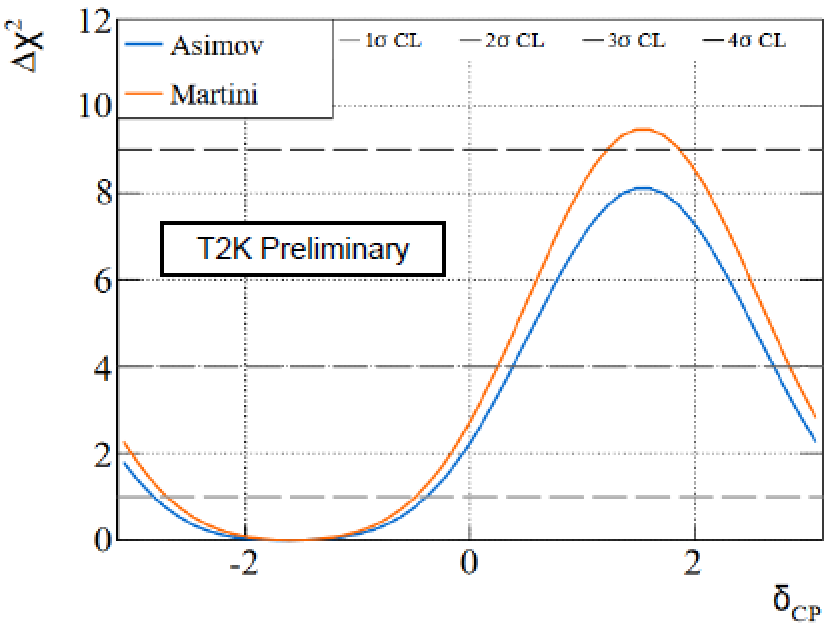


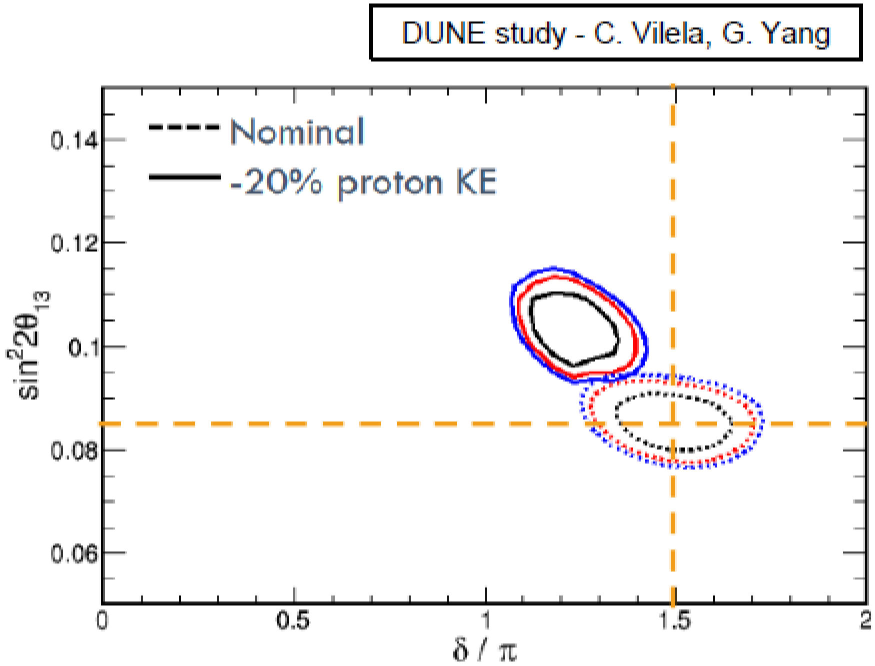
Martini et al., PRD 87 (2013)

Two-nucleon currents

- Large implications for oscillation measurements

Mock data studies





M. Scott

Photon emission in NC interactions

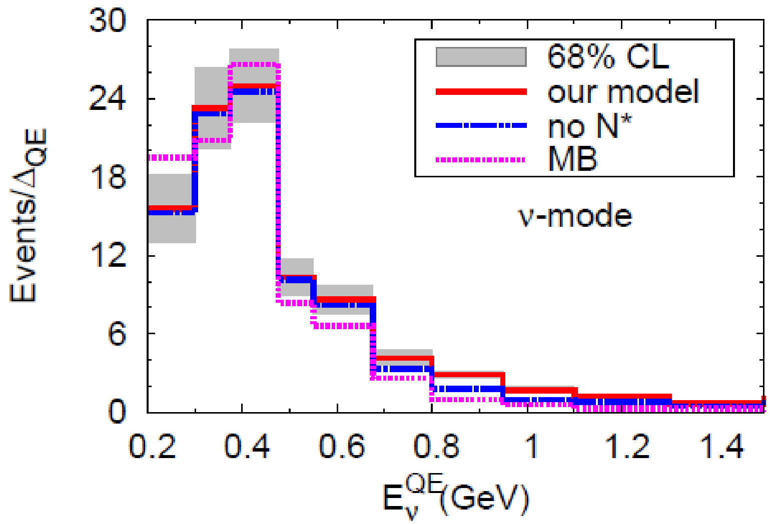
- on nucleons $\nu(\bar{\nu})\, N \rightarrow \nu(\bar{\nu})\, \gamma\, N$

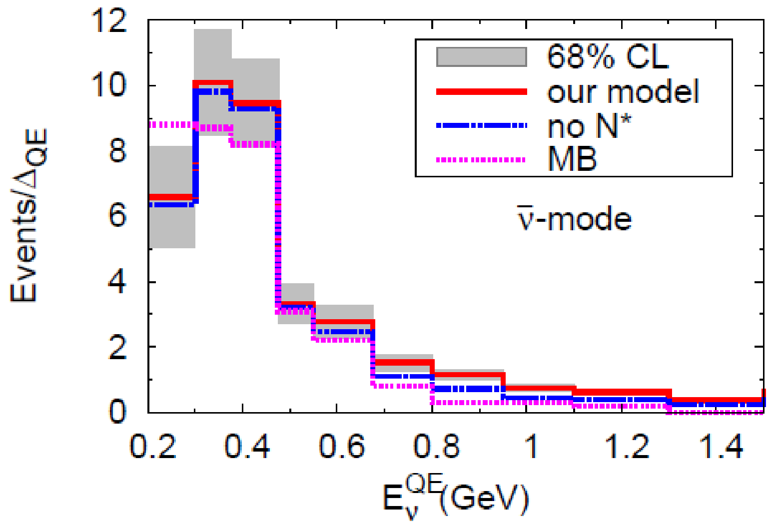
R. Hill, PRD 81 (2010)
Zhang & Serot, PRC 86 (2012)
Wang, LAR, Nieves, PRC 89 (2014)

- on nuclei $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, X$ ← incoherent

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

- Comparison to the MiniBooNE estimate E. Wang, LAR, J. Nieves, PLB 740 (2015)





- NCγ : insufficient to explain the excess of e-like events at MiniBooNE
- Same conclusion as Zhang, Serot, PLB 719 (2013)

Photon emission in NC interactions

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

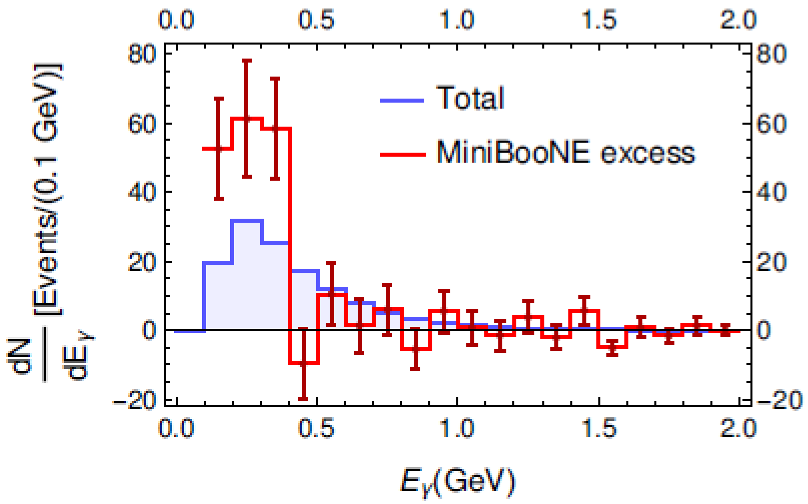
- on nucleons $\nu(\bar{\nu})\, N \to \nu(\bar{\nu})\, \gamma\, N$
- on nuclei $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$ ← incoherent

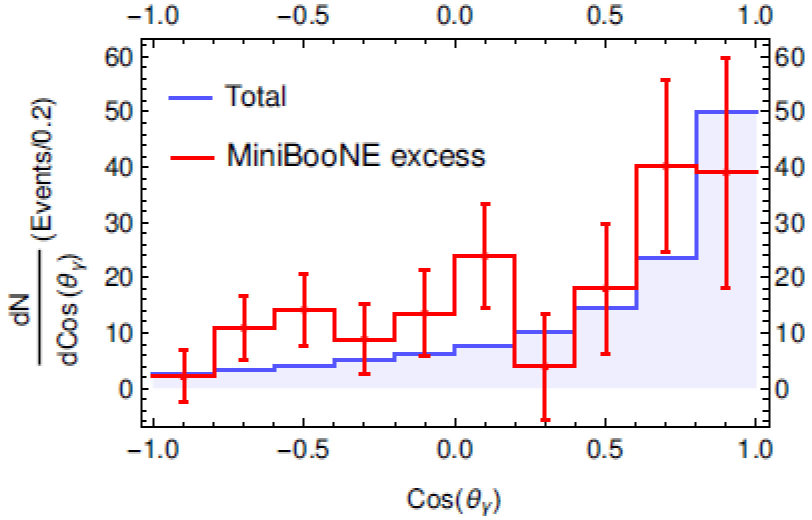
  $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, A$ ← coherent

- Heavy ($\sim$ 50 MeV) ν produced weakly or EM, followed by $\nu_h \to \nu\, \gamma$
  S. Gninenko, PRL 103 (2009), M. Masip et al, JHEP 1301 (2013)
  - Difficult to describe both E_γ and $\cos\theta_\gamma$ distributions

Events @ MiniBooNE

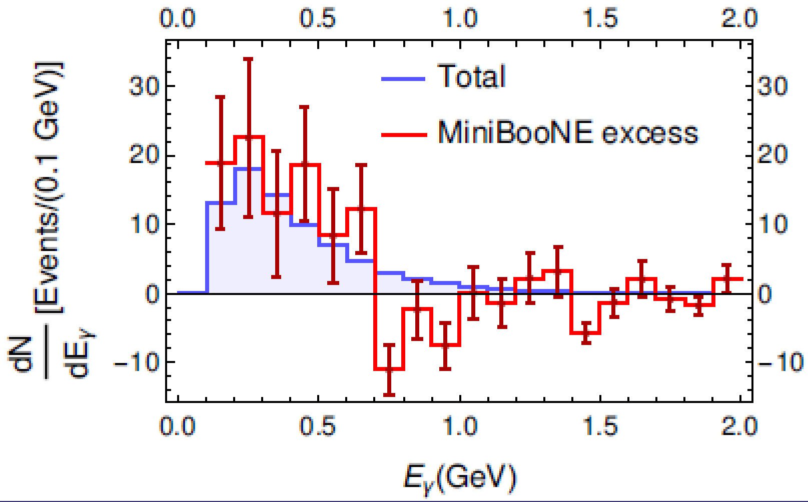
- ν mode

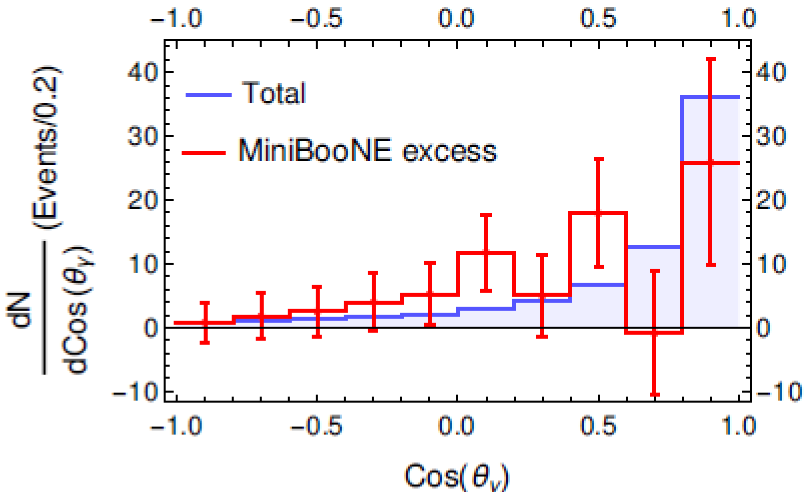




- $\bar{\nu}$ mode

LAR, E. Saúl Sala, in preparation, POS EPS-HEP (2017)





Photon emission in NC interactions

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

- on nucleons $\nu(\bar{\nu})\, N \to \nu(\bar{\nu})\, \gamma\, N$
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  $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, A$ $\leftarrow$ coherent

- Heavy ($\sim$ 50 MeV) ν produced weakly or EM, followed by $\nu_{\mathrm{h}} \to \nu\, \gamma$

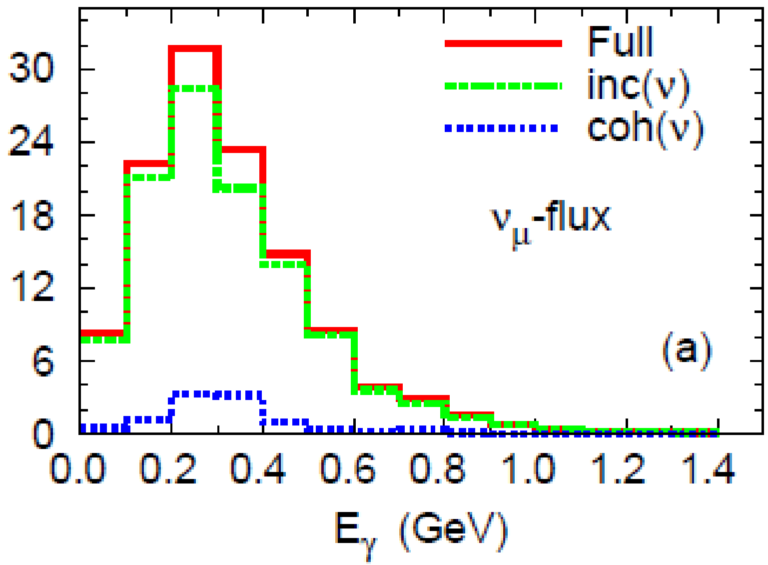
  S. Gninenko, PRL 103 (2009), M. Masip et al, JHEP 1301 (2013)

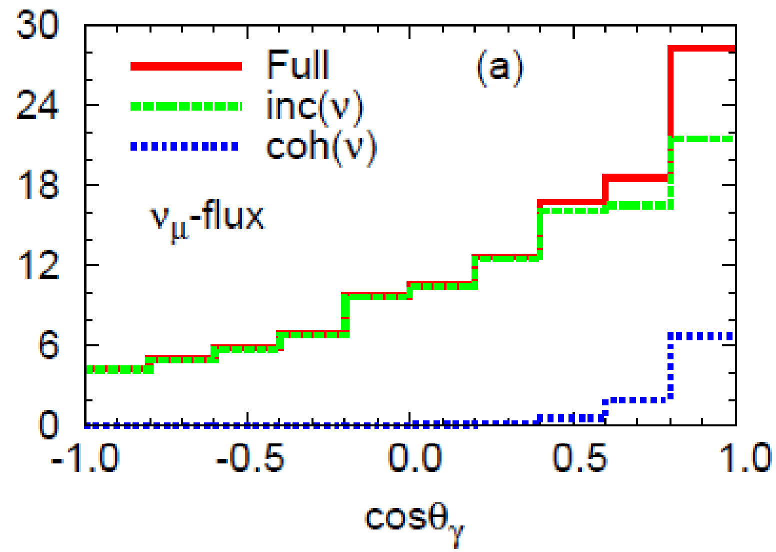
  - Difficult to describe both E_γ and $\cos\theta_\gamma$ distributions

- Ongoing NCγ analysis: MICROBOONE-NOTE-1041-PUB.pdf

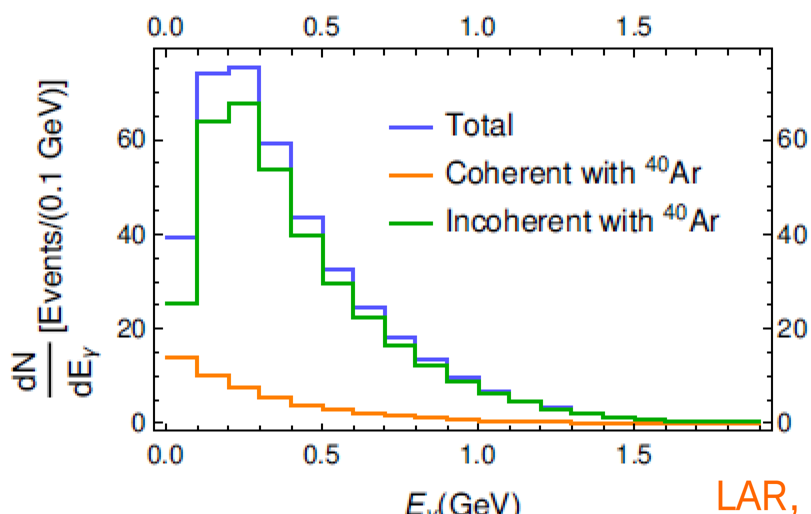
MicroBooNE

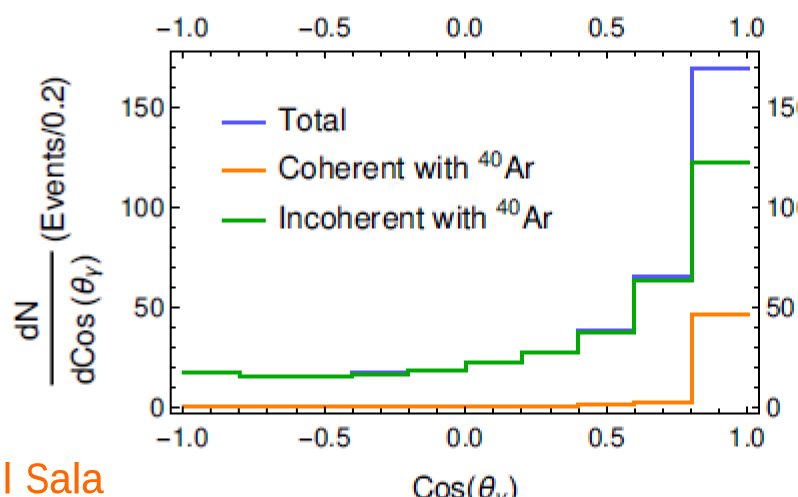
- SM prediction LAR, Wang





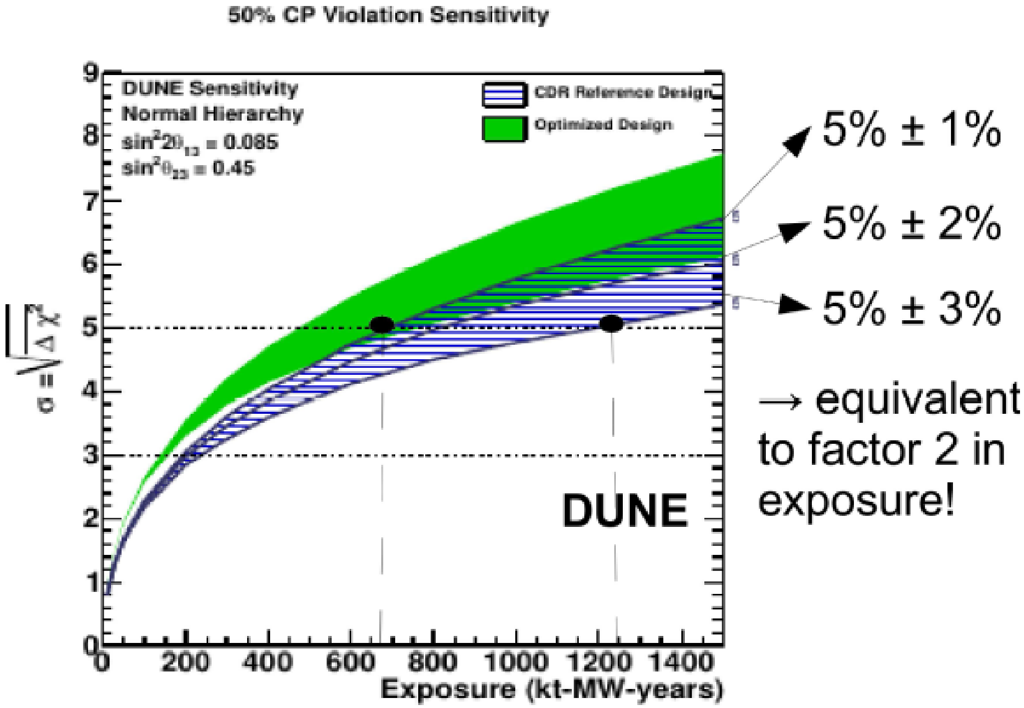
- $\nu_h \to \nu\,\gamma$





LAR, E. Saúl Sala

Conclusion



- Systematic errors are expensive

It is faster and cheaper to pay a theoretician to reduce 2 % your systematics than building new huge detectors!

G. D. Megias @ NuInt 2018