The 19th International Workshop on Neutrinos from Accelerators
NUFACT (2017)

Neutrino-nucleus scattering theory

Luis Alvarez Ruso

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 (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

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

ν cross section theory HOWTO

- Multiscale problem (even at a given E_ν)
- Perturbation theory is not aplicable (except close to thesholds and in the DIS regime)
- We rely on:
  - First principles: symmetries and basic properties of EW and strong int.
  - Phenomenological input: from photon, electron, meson (π) nucleon/nucleus scattering, decays, ...
  - Validation from non-ν reactions
- We study:
  - ν-nucleon interactions: elastic, quasi-elastic, inelastic (mostly meson production, mostly resonant), deep inelastic
  - *Nuclear effects*
    - Multi-nucleon problem
    - initial state description: non-relativistic *ab-initio* calculations, spectral functions, mean fields, collective effects
    - final state interactions: (relativistic) NN, πN, ...

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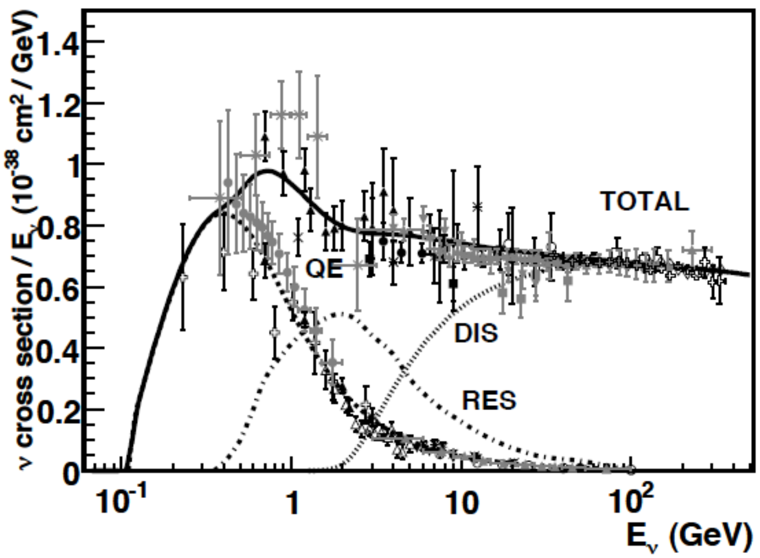
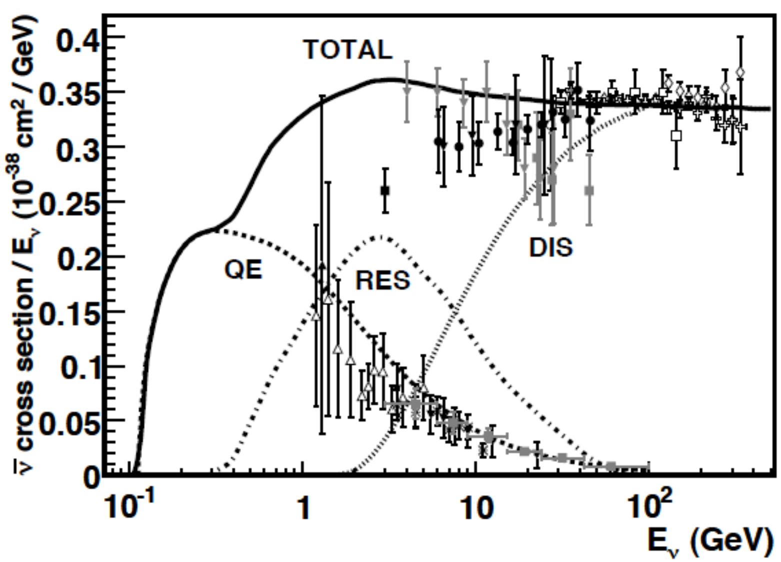


- nd basic properties of EW and strong int.
  photon, electron, meson (π)
  ecays, ...
  ns
-

  c, quasi-elastic, inelastic (mostly meson



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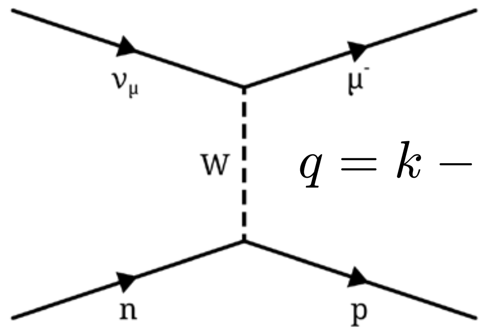
ν QE scattering on the nucleon

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



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

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

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

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

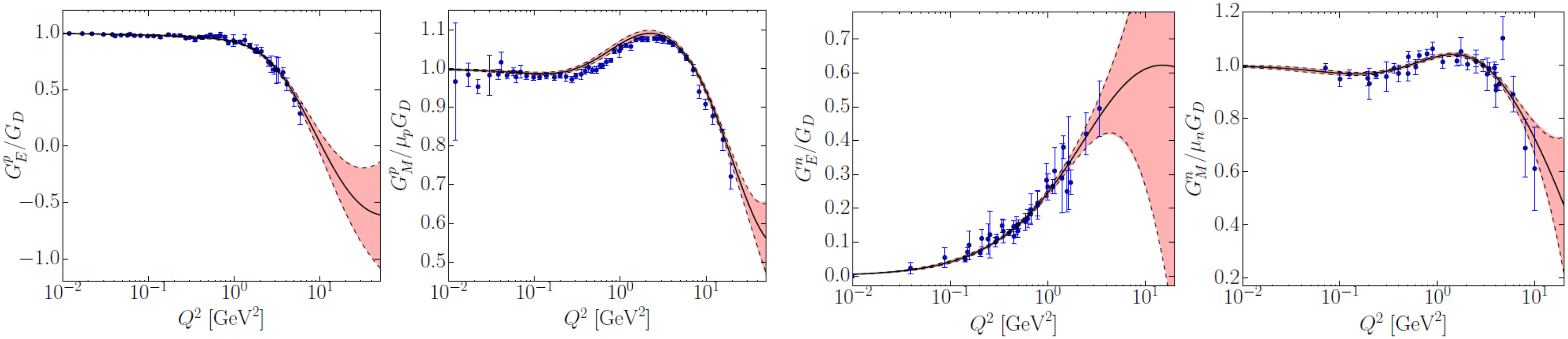
- Vector form factors: $F_{1,2}^V = F_{1,2}^p - F_{1,2}^n$

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

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

ν QE scattering on the nucleon

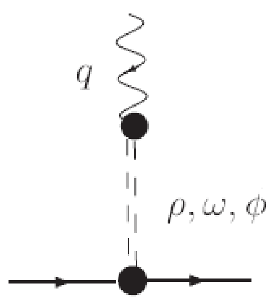
- EM form factors from (e,e') scattering



Ye et al., arXiv:1707.09063

- World data fitted with a bounded polynomial z-expansion
- Radiative and two-photon exchange corrections
- Dipole behavior for $Q^2 \lesssim 1$ GeV^2
  - (In principle) not theoretically justified
  - Exponential charge distributions (in the static limit)
  - In the VMD picture, a dipole might arise from two mesons with similar masses and opposite couplings

$$G_D = \left(1 + \frac{Q^2}{0.71\,\mathrm{GeV}^2}\right)^{-2}$$

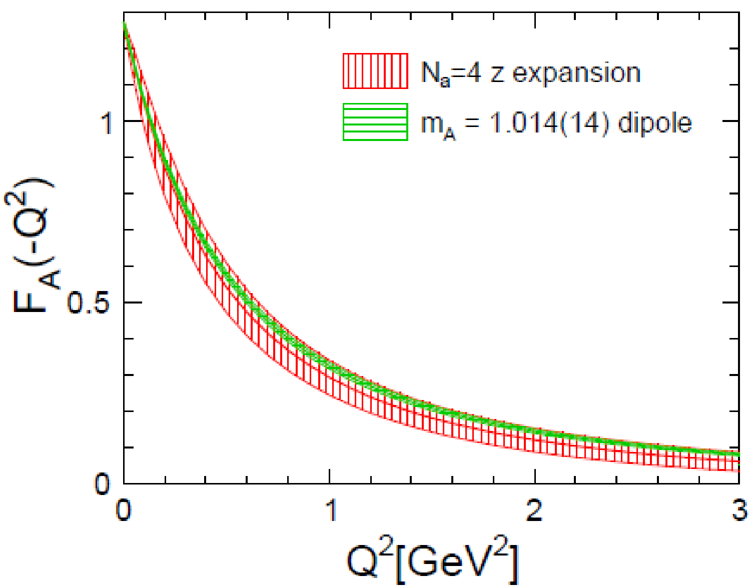


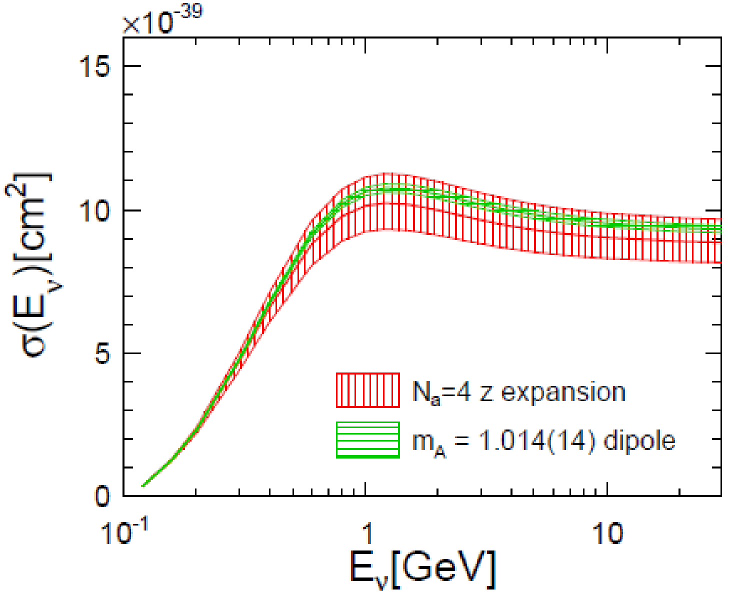
QE scattering on the nucleon

- Dipole ansatz:

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

  - (In principle) 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





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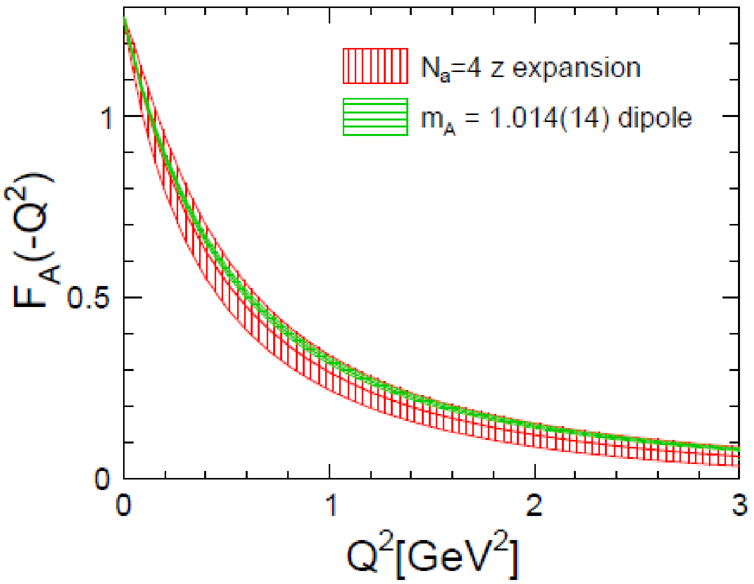
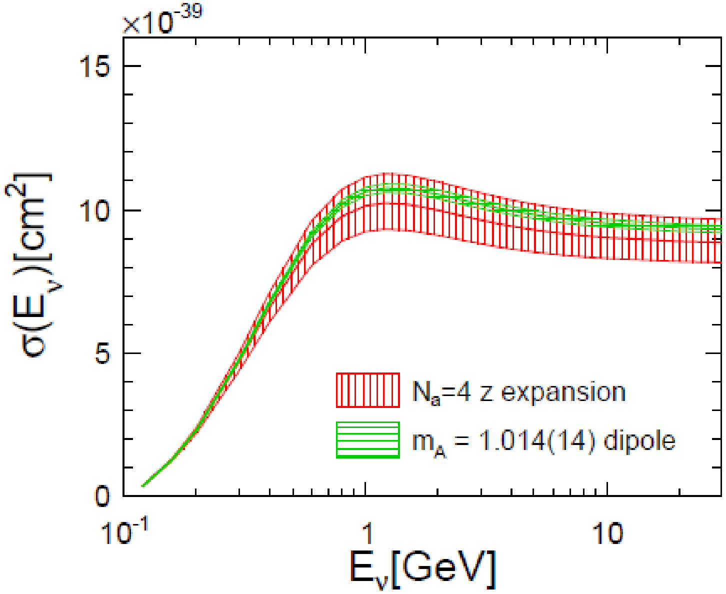
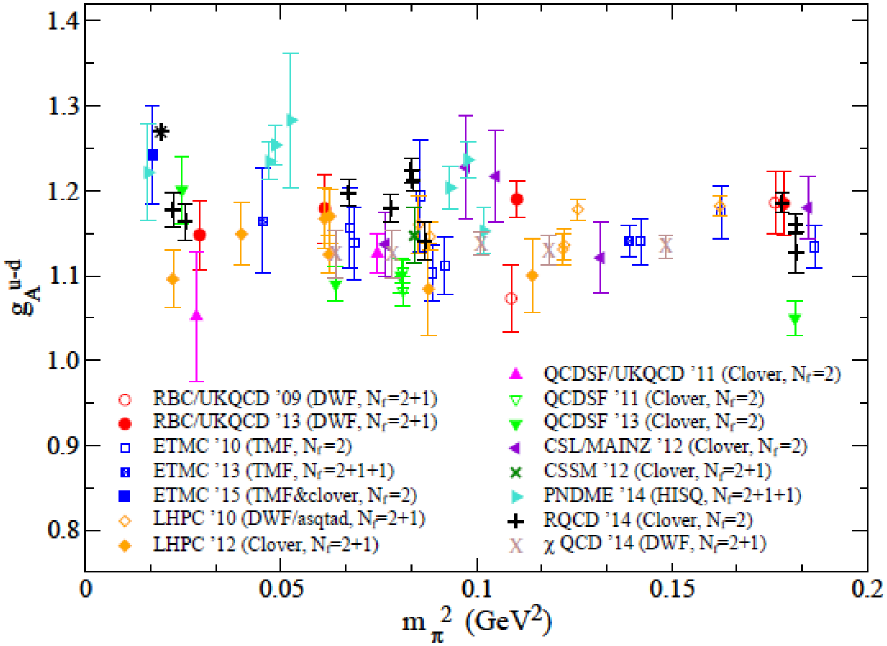




- $\langle r_A^2 \rangle$ = 0.46(22) fm^2 vs 0.453(12) fm^2 Bodek et al., EPJC 53 (2008)
- At $E_\nu \sim 1$ GeV σ(CCQE) has ≈ 10 % error
- More precise information about F_A is needed
  - Lattice QCD

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

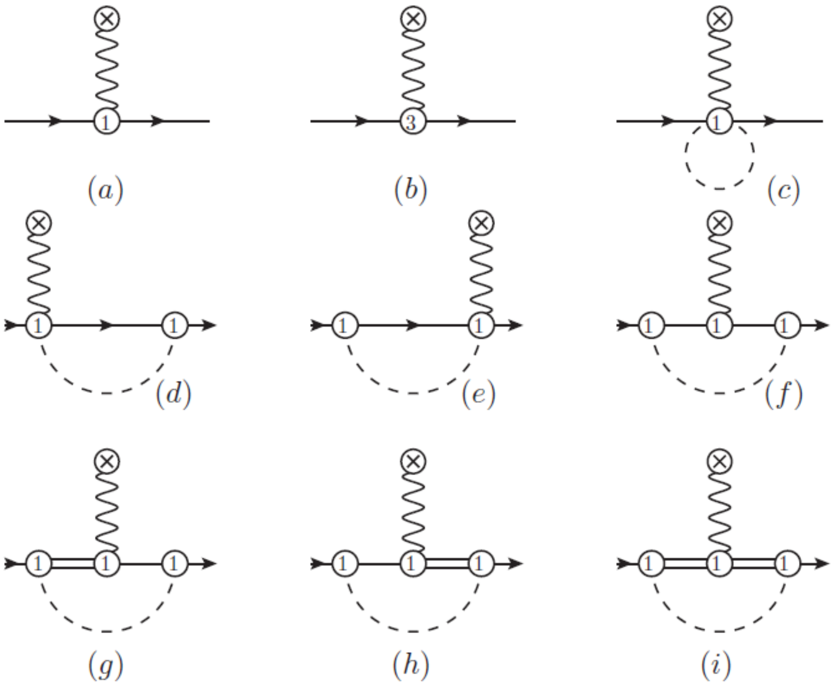
Alexandrou et al., Phys. Rev. D 96 (2017)
Capitani et al., arXiv:1705.06186
Gupta, arXiv:1705.06834

F_A & LQCD

- Recent progress:

  Alexandrou et al., Phys. Rev. D 96 (2017)
  Capitani et al., arXiv:1705.06186
  Gupta et al., arXiv:1705.06834

- Baryon ChPT analysis: Yao, LAR, Vicente Vacas, arXiv:1708.0877
  - $O(p^3)$, $Q^2 < 0.36$ GeV^2, 130 MeV $< M_\pi <$ 473 MeV, explicit $\Delta(1232)$



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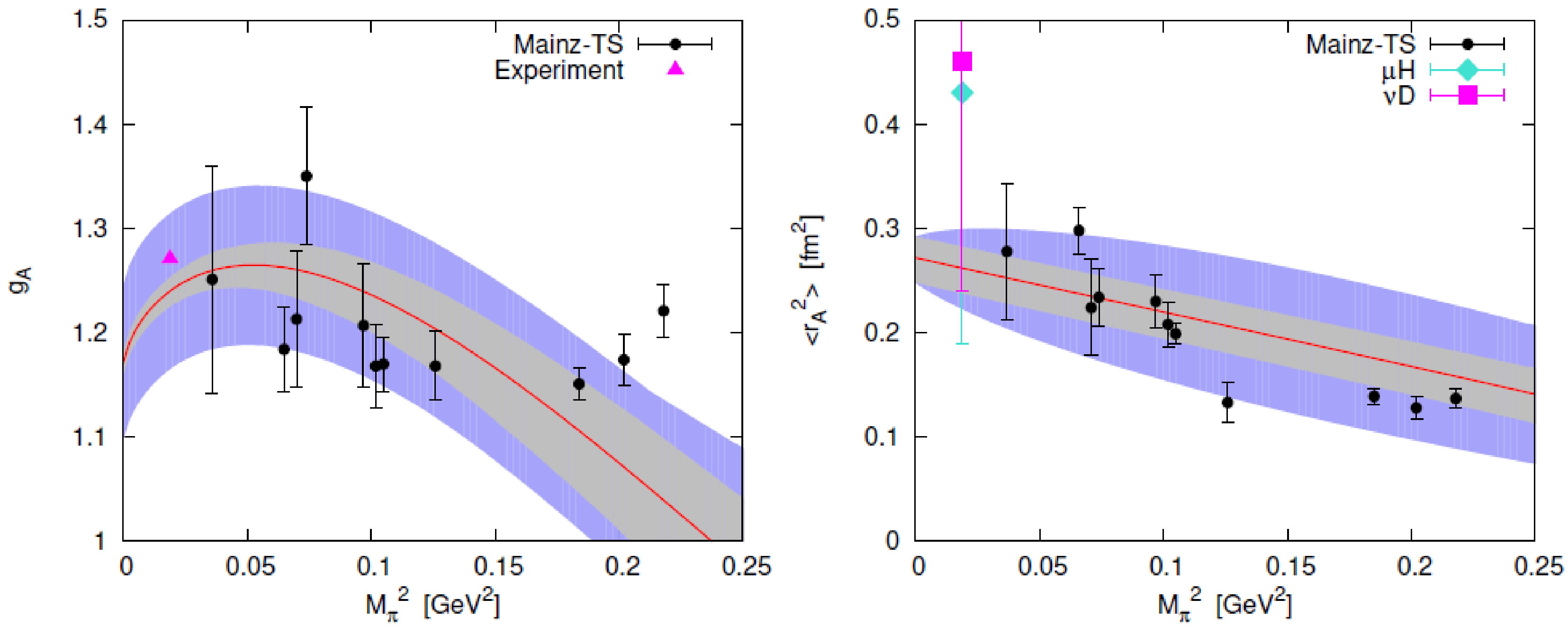

  - $g_A = 1.237(74)$, $<r_A^2> = 0.263(38)$ fm^2

F_A & LQCD

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- Improvements:
  - BChPT: $O(p^5)$ might be needed to improve M_π dependence
  - LQCD: excited states and finite volume corrections
    - Critical to reliably obtain F_A in LQCD

QE scattering on the nucleon

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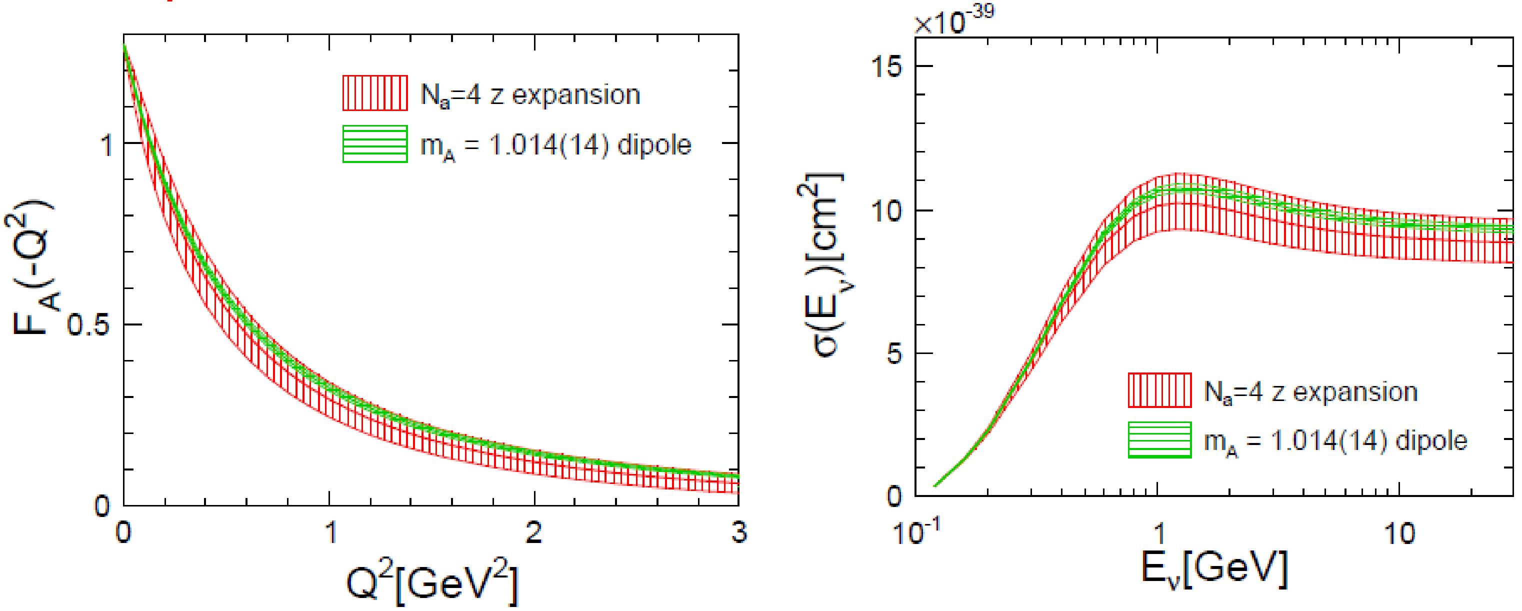

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- At $E_\nu \sim 1$ GeV σ(CCQE) has $\approx$ 10 % error
- More precise information about F_A is needed
  - Lattice QCD
  - Direct or indirect CCQE measurement on n/p

CCQE production of hyperons

- $W^- \; u \to s \quad \sim \sin\theta_c$

$$\bar\nu(k) + p(p) \;\rightarrow\; l^+(k') + \Lambda, \Sigma^0(p')$$
$$\bar\nu(k) + n(p) \;\rightarrow\; l^+(k') + \Sigma^-(p')$$

Singh, Vicente Vacas, PRD74 (2006)

$$\mathcal{M} = \frac{G_F \sin\theta_C}{\sqrt{2}} l^\alpha J_\alpha \qquad J_\alpha = \mathcal{V}_\alpha - \mathcal{A}_\alpha$$

$$\mathcal{V}^\alpha = \bar u_Y(p') \left[\gamma^\alpha f_1 + \frac{i}{M+M_Y}\sigma^{\alpha\beta} q_\beta f_2 + \frac{q^\alpha}{M_Y} f_3\right] u(p)$$
$$\mathcal{A}^\alpha = \bar u_Y(p') \left[\gamma^\alpha \gamma_5 g_1 + \frac{i}{M+M_Y}\sigma^{\alpha\beta} q_\beta \gamma_5 g_2 + \frac{q^\mu}{M_Y} \gamma_5 g_3\right] u(p)$$

- SU(3) symmetry: $f_3 = g_2 = 0$, $f_{1,2} \Leftrightarrow F_{1,2}$, $g_{1,3} \Leftrightarrow F_{A,P}$
- SU(3) breaking corrections can be studied with ChPT
  Zhu, Puglia, Ramsey-Musolf, PRD63 (2001)
- Source of pions: Y $\to$ N π

CCQE production of hyperons

- $W^- \; u \rightarrow s \qquad \sim \sin\theta_c$

$$\begin{aligned} \bar{\nu}(k) + p(p) &\rightarrow l^+(k') + \Lambda, \Sigma^0(p') \\ \bar{\nu}(k) + n(p) &\rightarrow l^+(k') + \Sigma^-(p') \end{aligned}$$

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$$\mathcal{M} = \frac{G_F \sin\theta_C}{\sqrt{2}} l^\alpha J_\alpha \qquad J_\alpha = \mathcal{V}_\alpha - \mathcal{A}_\alpha$$

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- Source of pions: Y $\rightarrow$ N π
- Establishing priorities (in a quantitative way) is very important

1π production on the nucleon

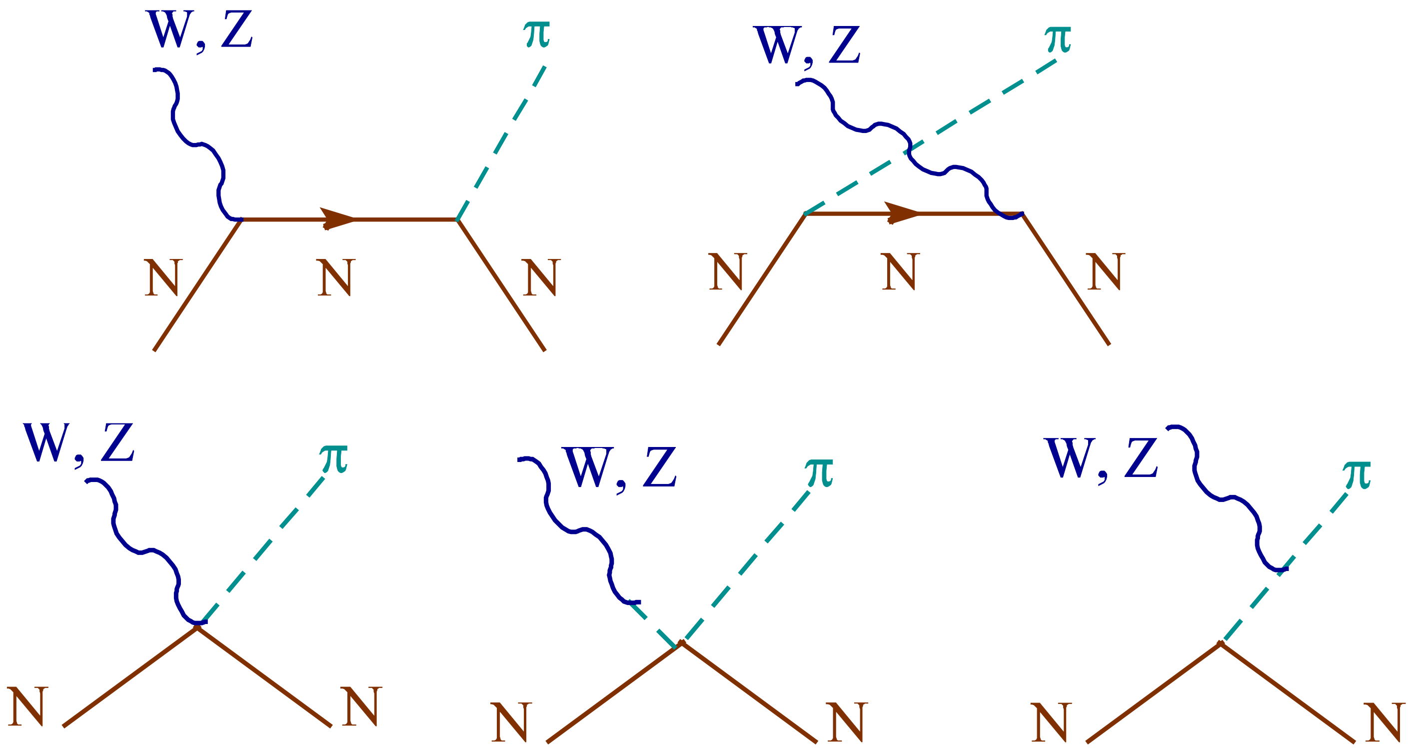
$$\nu_l \, N \to l \, \pi \, N'$$

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

1π production on the nucleon

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

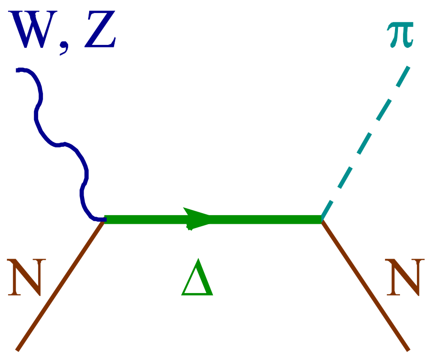
- From Chiral symmetry:



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

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

$$C_5^A(0) = \sqrt{\frac{2}{3}}\, g_{\Delta N\pi}$$ $\leftarrow$ off diagonal Goldberger-Treiman relation

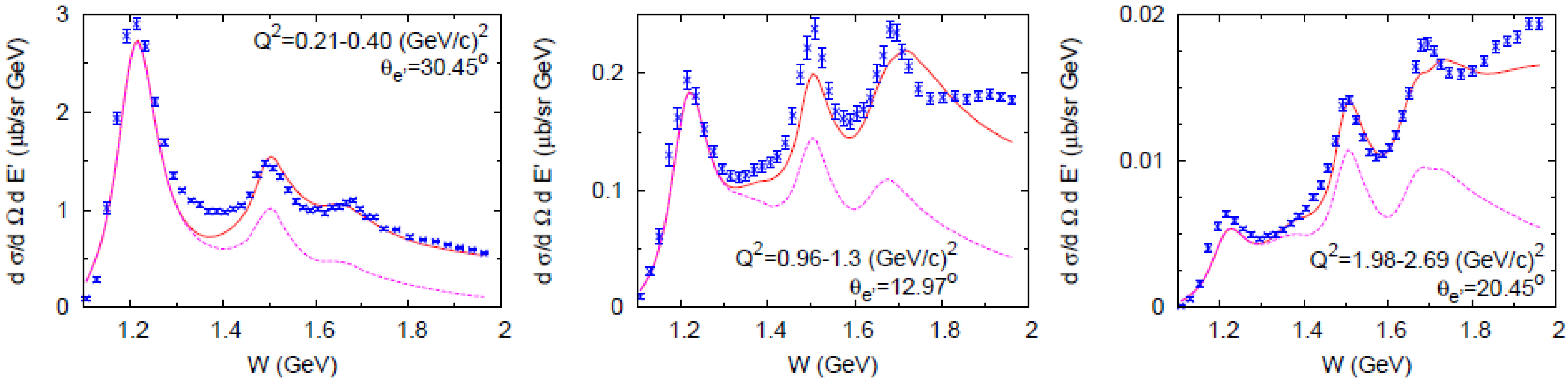
$$\mathcal{L}_{\Delta N\pi} = -\frac{g_{\Delta N\pi}}{f_\pi}\bar{\Delta}_\mu(\partial^\mu \vec{\pi})\vec{T}^\dagger N \qquad g_{\Delta N\pi} \Leftrightarrow \Gamma(\Delta \to N\pi)$$

- Deviations from GTR arise from chiral symmetry breaking
  - expected only at the few % level
- Reconciling GTR with the ANL and BNL data on $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$
  - Unitarization in the leading vector and axial multipoles

LAR, Hernandez, Nieves, Vicente Vacas, PRD 93 (2016)

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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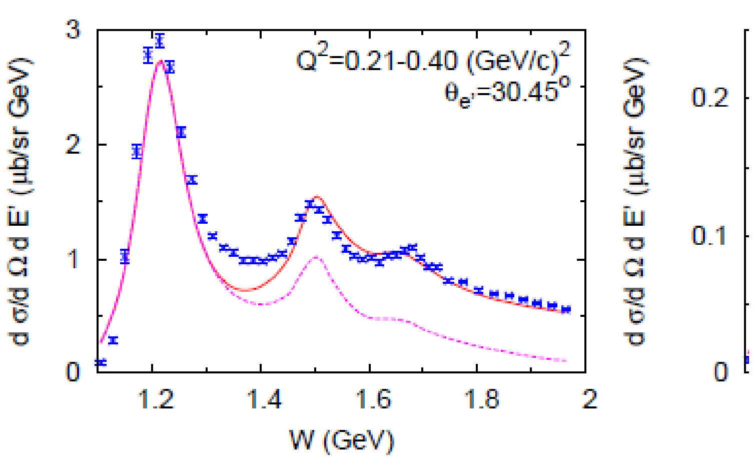
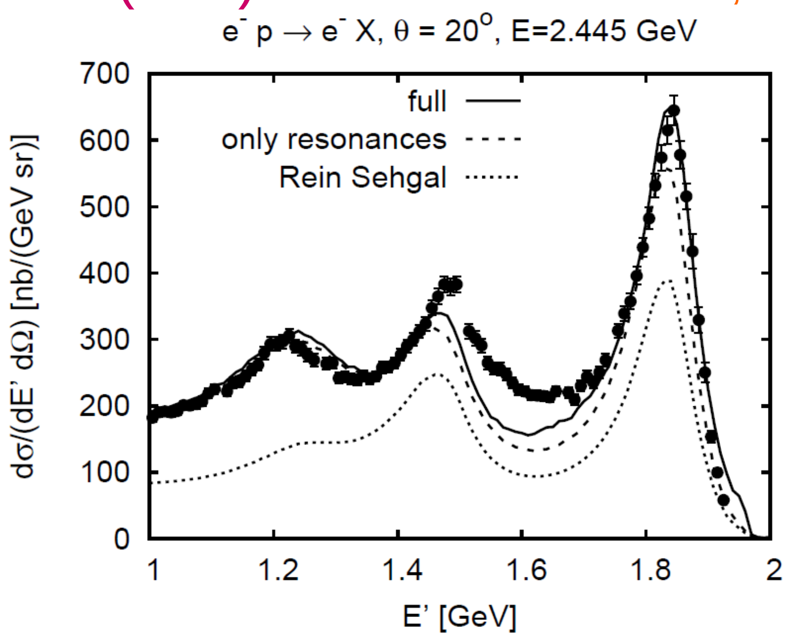
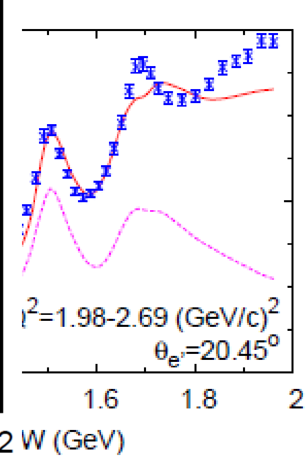




T. Leitner, PhD thesis (2009)



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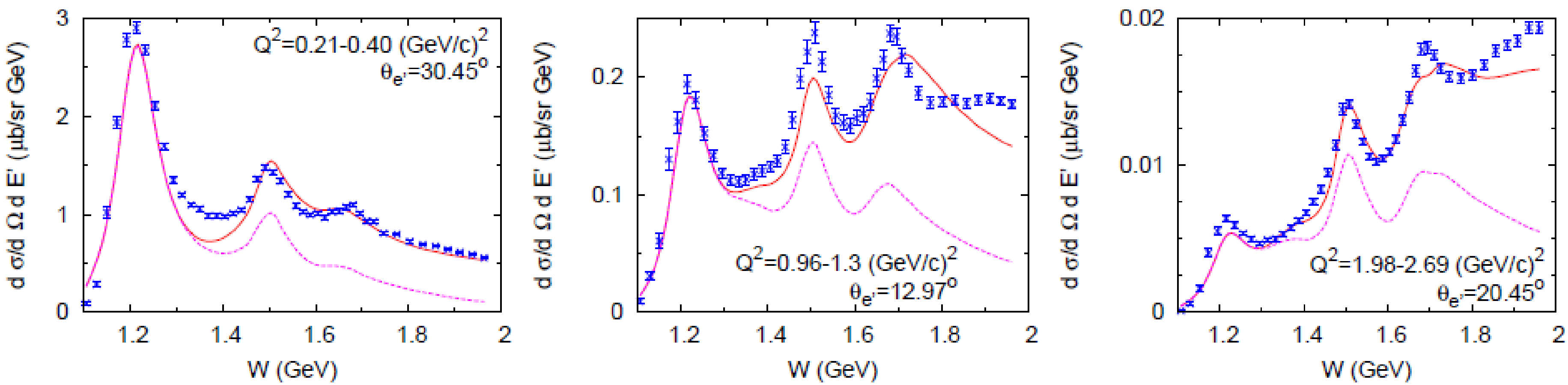

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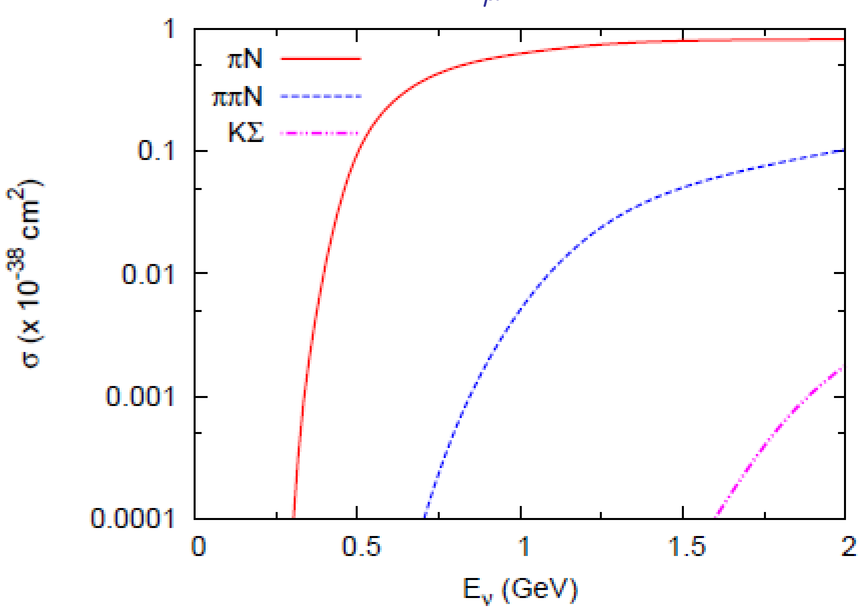
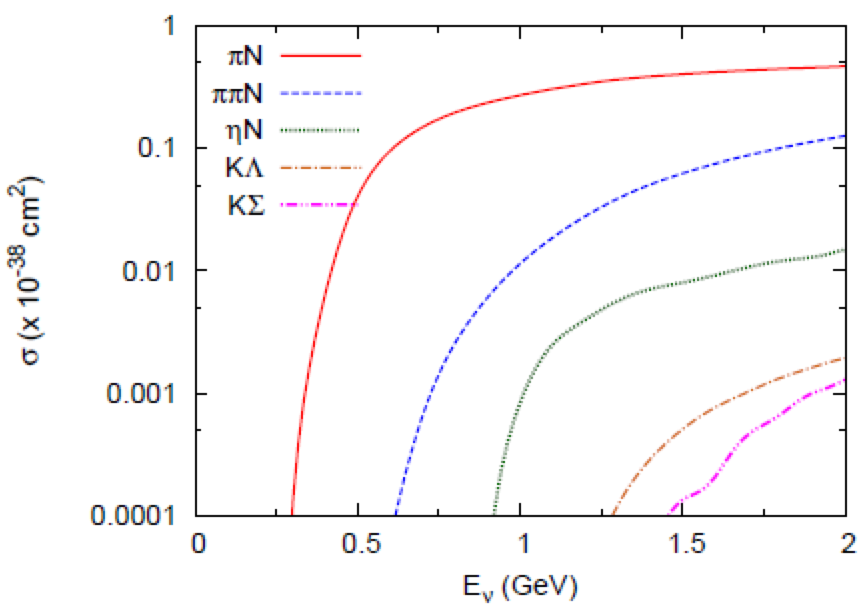
ν_μ p $\rightarrow$

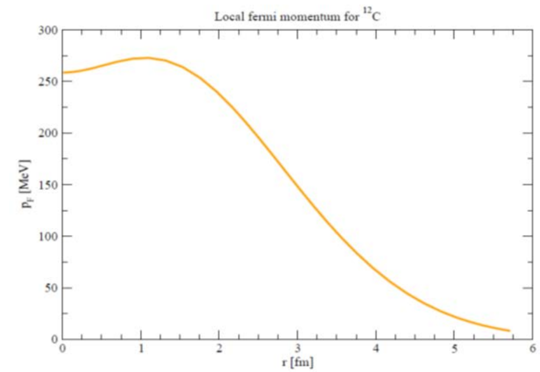


ν_μ n $\rightarrow$



1π production on nuclei

- 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

1π production on nuclei

- 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 $\Delta \to N \pi$ modified by Pauli blocking

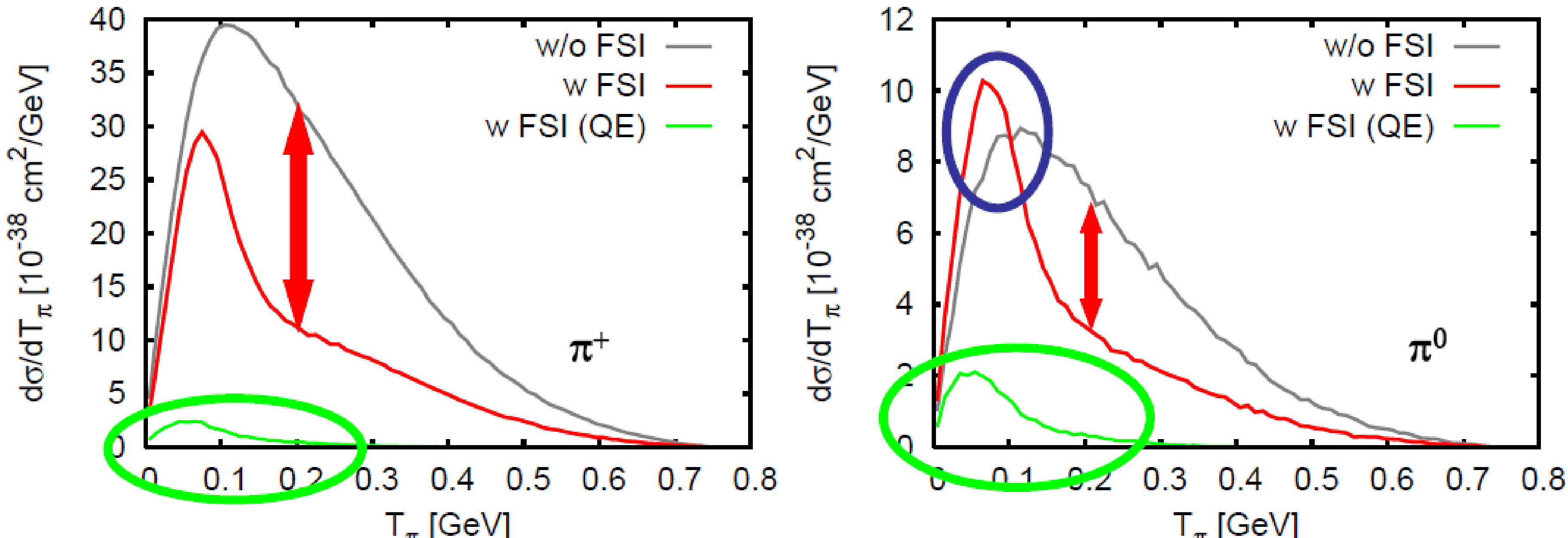
$$\mathrm{Re}\Sigma_\Delta(\rho) \approx 40\mathrm{MeV}\frac{\rho}{\rho_0}$$

$\mathrm{Im}\Sigma_\Delta(\rho) \leftarrow$

- Δ N $\to$ N N
- Δ N $\to$ N N π
- Δ N N $\to$ N N N

1π production on nuclei

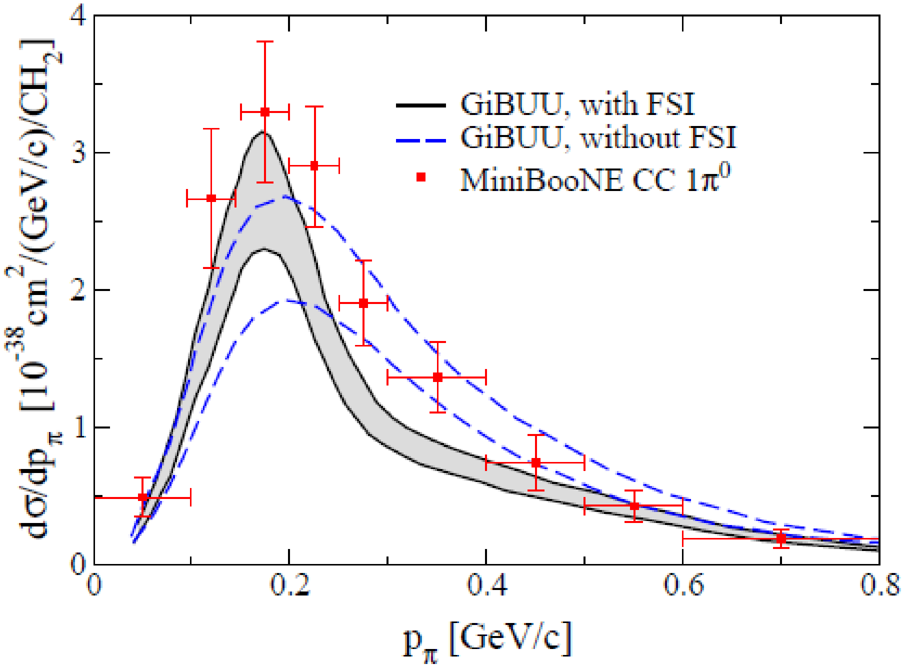
- GiBUU Leitner, LAR, Mosel, PRC 73 (2006)
  - Effects of FSI on pion kinetic energy spectra
    - strong absorption in Δ region
    - side-feeding from dominant π^+ into π^o channel
    - secondary pions through FSI of initial QE protons



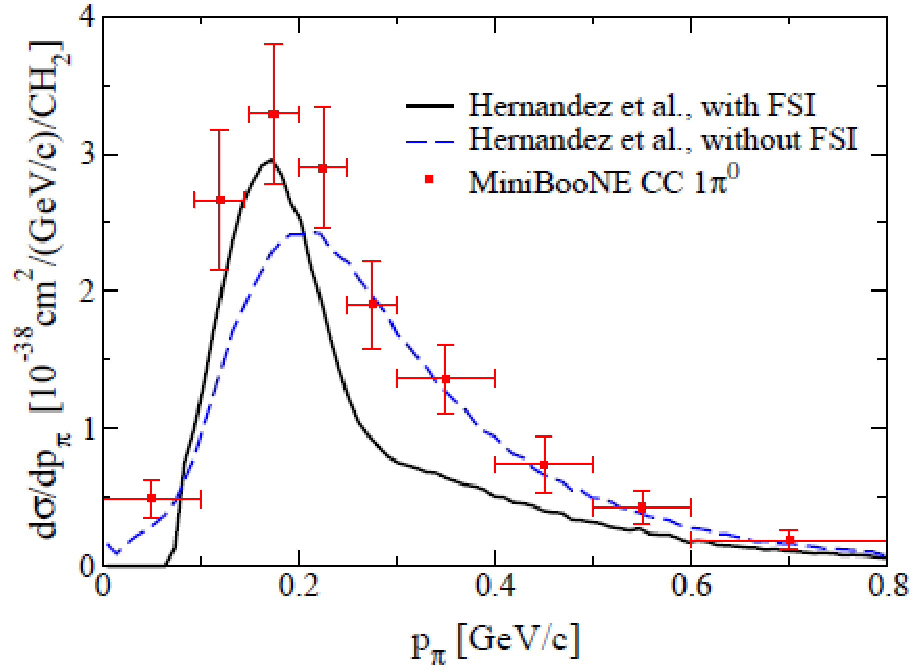
$$\nu_\mu + {}^{56}Fe \to \mu^- \, \pi \, X \quad E_\nu = 1 \text{ GeV}$$

1π production on nuclei

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



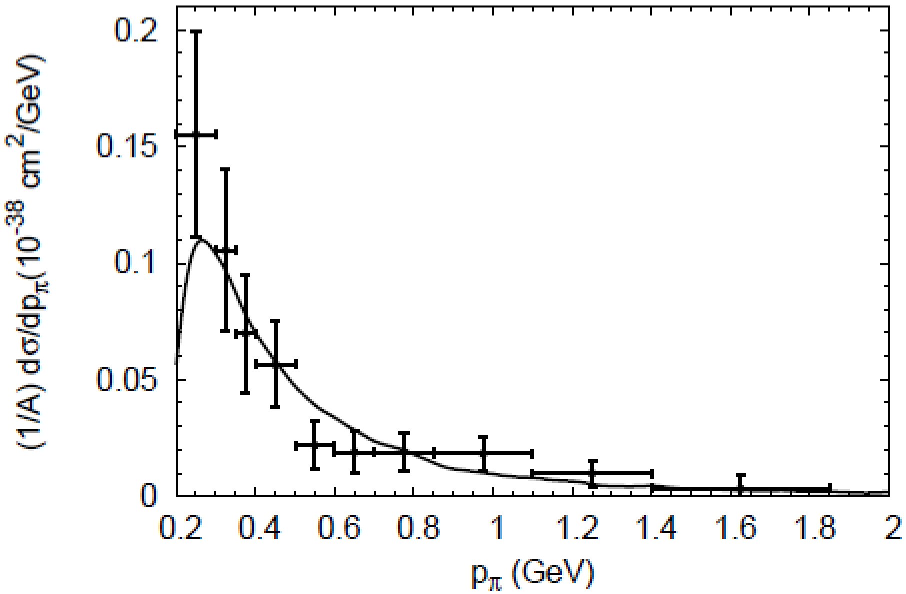
Hernandez et al., PRD87 (2013)



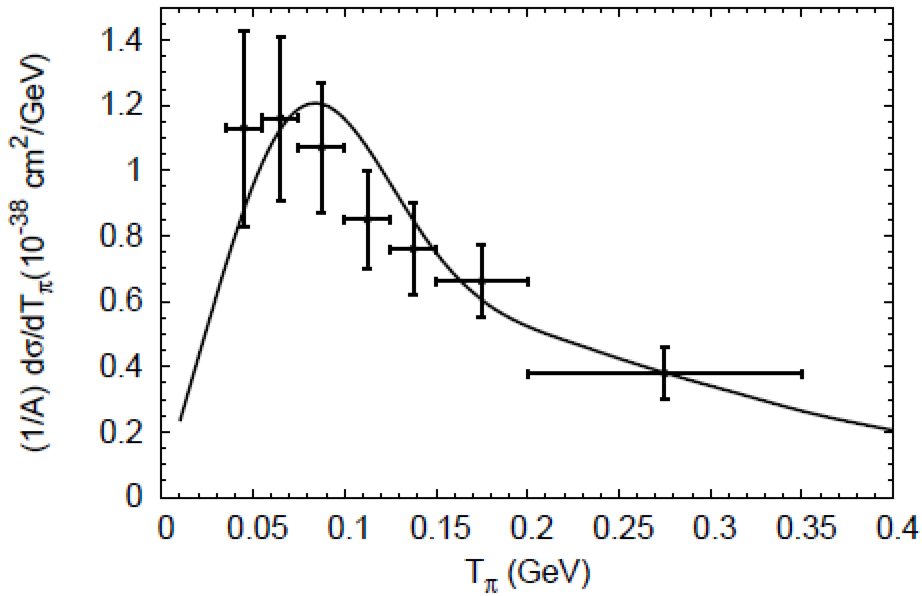
Lalakulich, Mosel, PRC87 (2013)

1π production on nuclei

Comparison to T2K (ND280): CCπ^+
Abe et al., PRD 95 (2017)



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



Mosel, Gallmeister, PRC96 (2017)

Photon emission in NC interactions

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

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

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

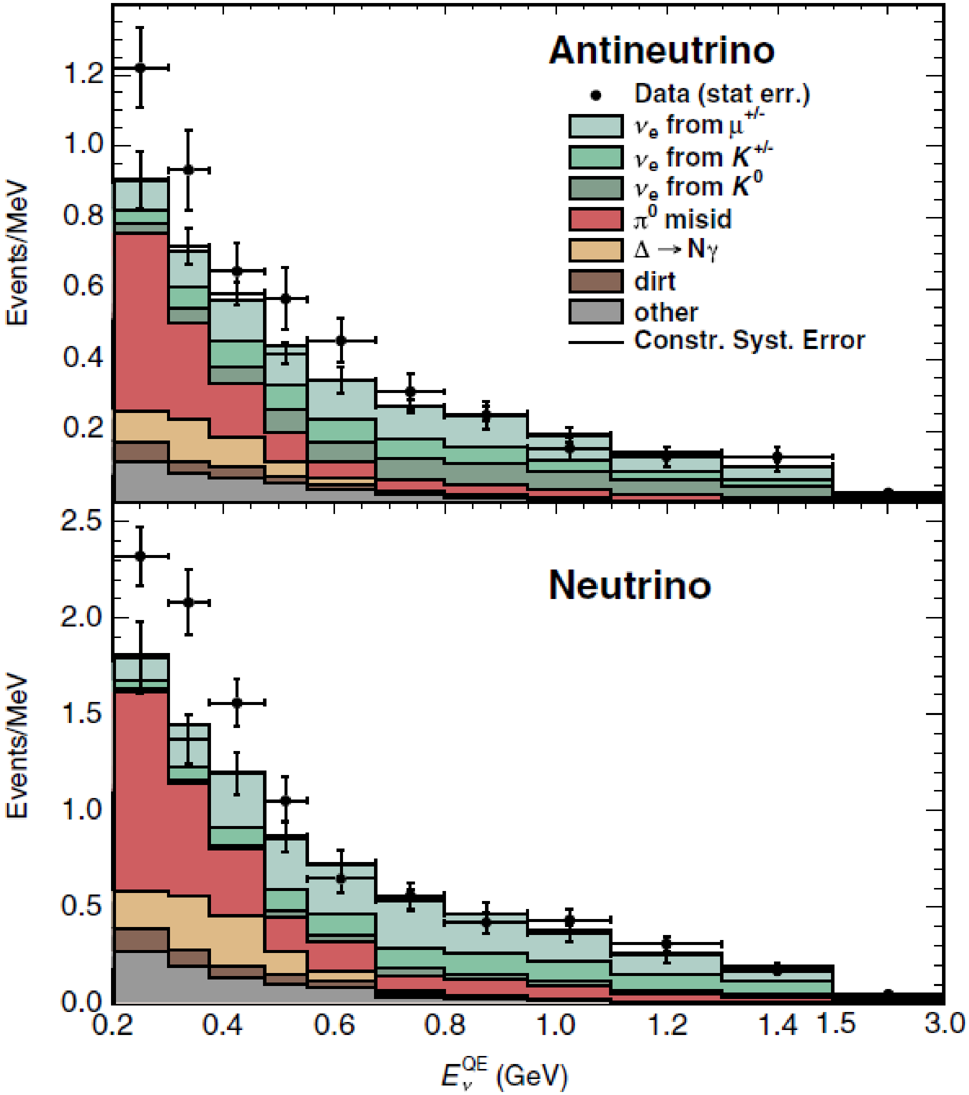
  but

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

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

MiniBooNE anomaly

- e-like events in the MiniBooNE $\nu_\mu \to \nu_e$ / $\bar{\nu}_\mu \to \bar{\nu}_e$ search:

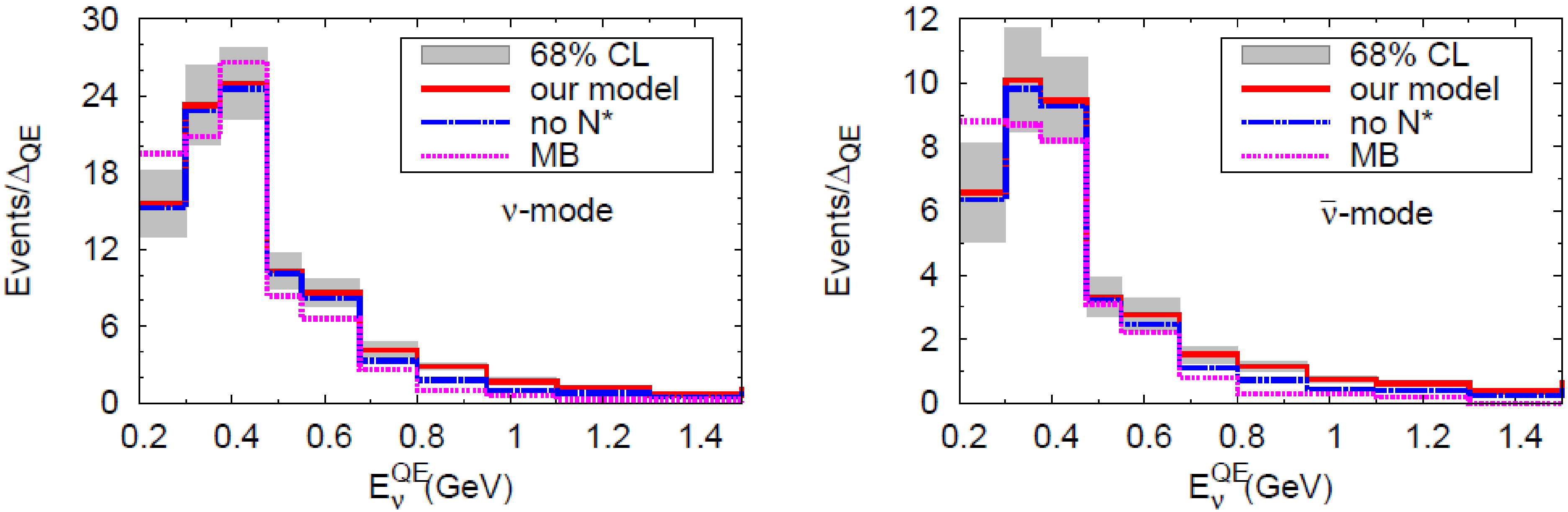


reconstructed ν energy

$$E_\nu^{QE} = \frac{2m_n E_e - m_e^2 - m_n^2 + m_p^2}{2(m_n - E_e + p_e \cos\theta_e)}$$

NCγ events at MiniBooNE

- Comparison to the MiniBooNE estimate
  - Resonance model (R&S) tuned to π production data
  - Only $R \to N\gamma$



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

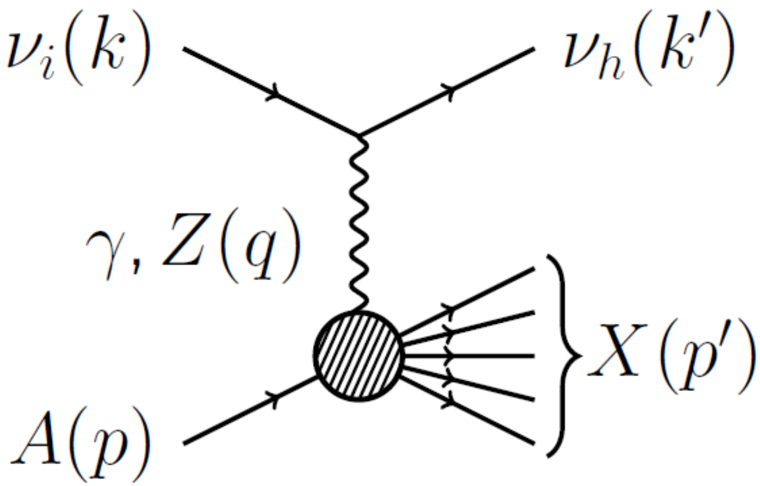
- NCγ : insufficient to explain the excess of e-like events at MiniBooNE
- Same conclusion as Zhang, Serot, PLB 719 (2013)

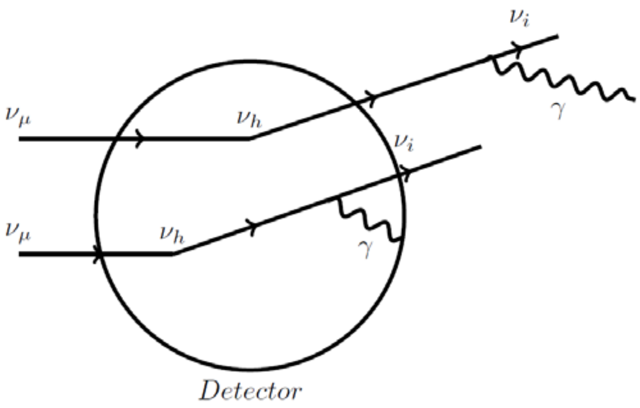
NCγ events at MiniBooNE

- Origin of e-like event excess @ 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)
    - Even after taking into account multi-nucleon interactions in E_ν reconstruction Ericson et al., Phys.Rev. D93 (2016)
  - Heavy ($\sim$ 50 MeV) ν produced weakly or EM, followed by $\nu_h \rightarrow \nu\,\gamma$

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

ν_h production and radiative decay





- on nucleons $\nu_\mu(\bar{\nu}_\mu)\, N \to \nu_h(\bar{\nu}_h)\, N$
- on nuclei $\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, A$ $\leftarrow$ coherent

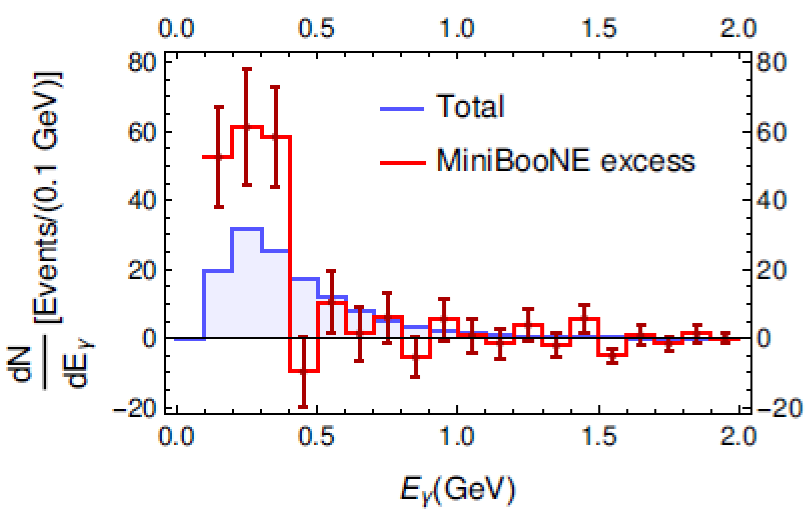
  $\nu_\mu(\bar{\nu}_\mu)\, A \to \nu_h(\bar{\nu}_h)\, X$ $\leftarrow$ incoherent

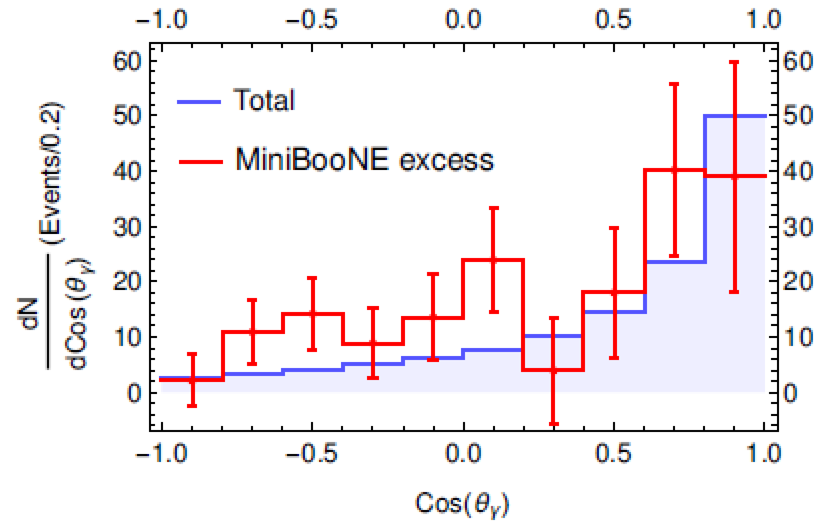
- ν_h= Dirac ν with m $\approx$ 50 MeV, slightly mixed with ν_μ
- A = ^{12}C (MiniBooNE, CH_2), ^{40}Ar (SBN program: SBND, MicroBooNE, Icarus)

LAR, E. Saúl Sala, in preparation, arXiv:1705.00353

Events @ MiniBooNE

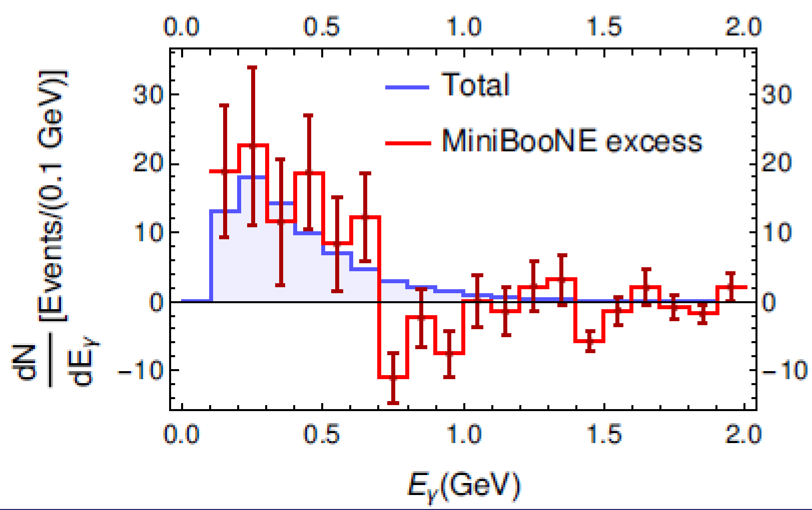
- ν mode

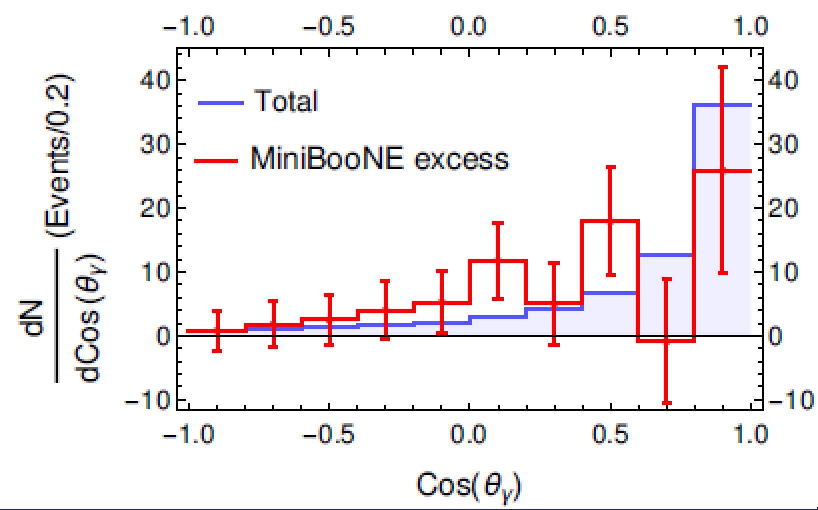




- $\bar{\nu}$ mode

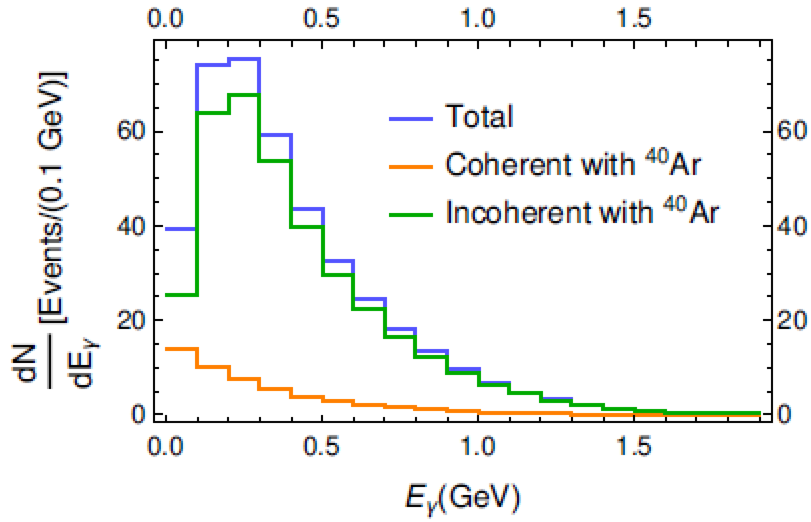
LAR, E. Saúl Sala, in preparation, arXiv:1705.00353

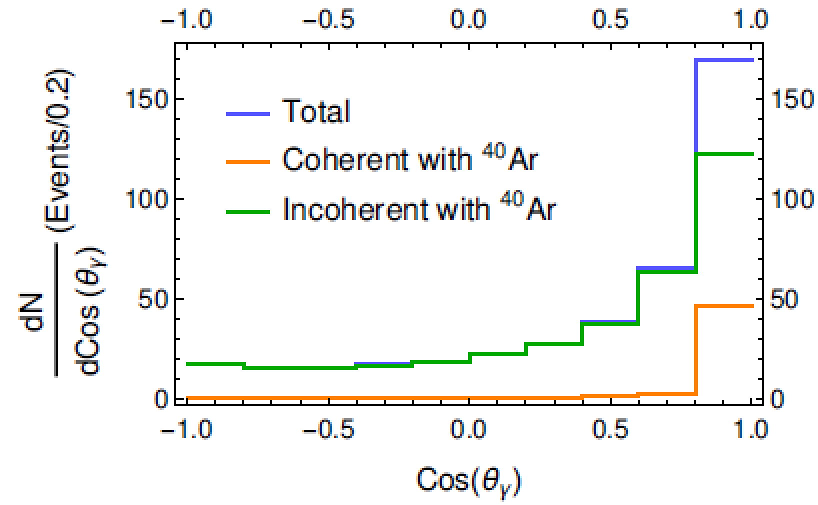




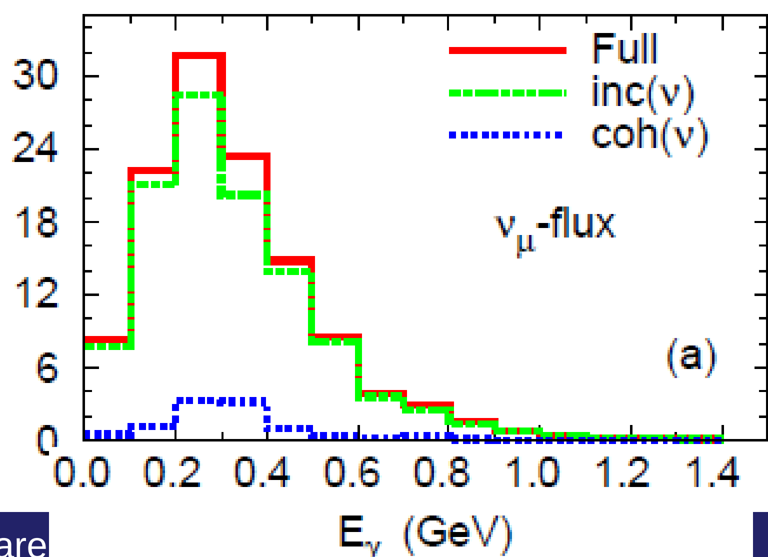
Events @ MicroBooNE

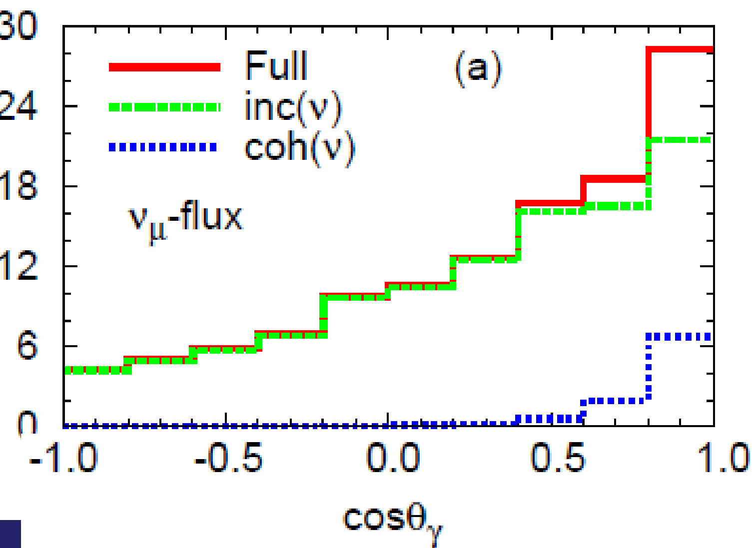
- ν mode





- SM prediction LAR & Wang

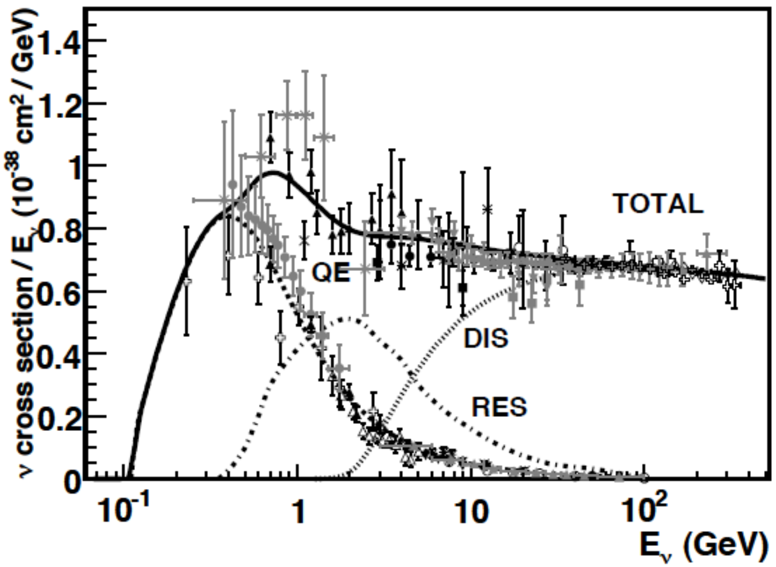




Not covered in this talk

- ν-nucleus QE(-like) scattering
  - MiniBooNE CCQE measurement actually contained a sizable contribution from 2p2h (Martini, ...)
  - Implications for E_ν reconstruction
  - WG2: Lovato, González Jiménez, Barbaro, Rocco, Sobczyk
  - WG2 Summary

Not covered in this talk



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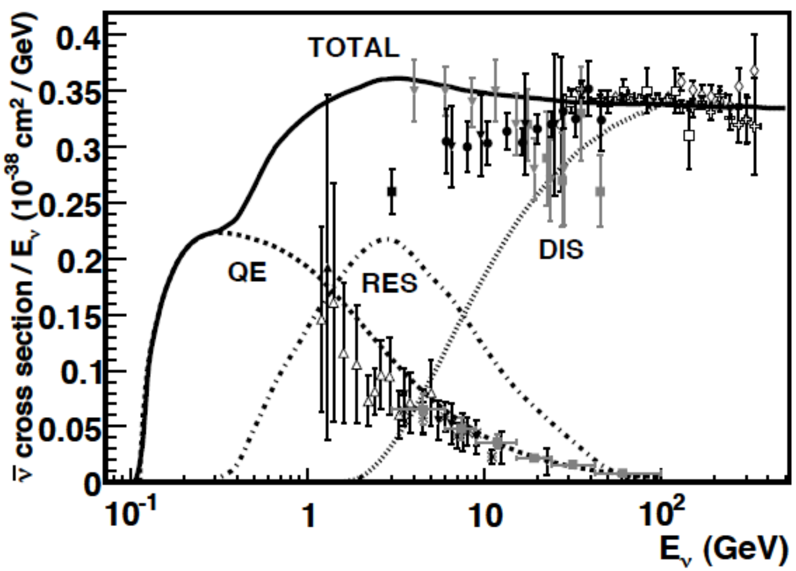

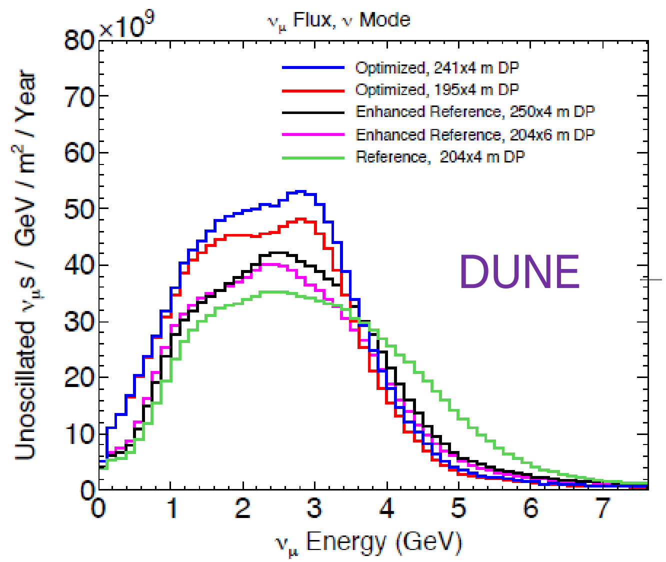

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  - WG2 Summary

- Shallow and Deep inelastic scattering
  - Onset of DIS: usually W>2 GeV, $Q^2 > 1$ GeV^2
  - At lower W, Q^2 : higher twists
  - Non trivial RES $\rightarrow$ DIS transition
  - Hadronization model needed to describe exclusive hadron production
  - Nuclear corrections

Final Word

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

NuSTEC Training in Neutrino-Nucleus Scattering Physics 2017

http://nustec.fnal.gov/school2017/

Fermilab, November 7-15, 2017

- Theory lectures (mainly) for (young) experimentalists