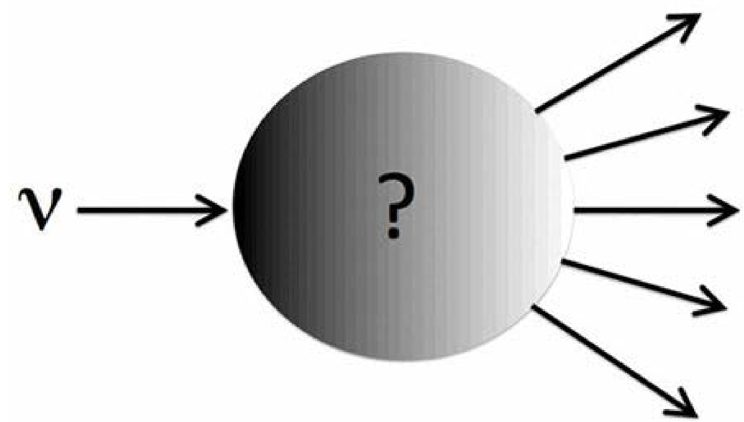
INT December 3-13, 2013

Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiments



Photon Emission in NC interactions with nucleons and nuclei

L. Alvarez-Ruso, J. Nieves, E. Wang

IFIC, Valencia

Introduction

- 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

$$\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, A'^{*}\, N'$$

$$\hookrightarrow \gamma\, A$$

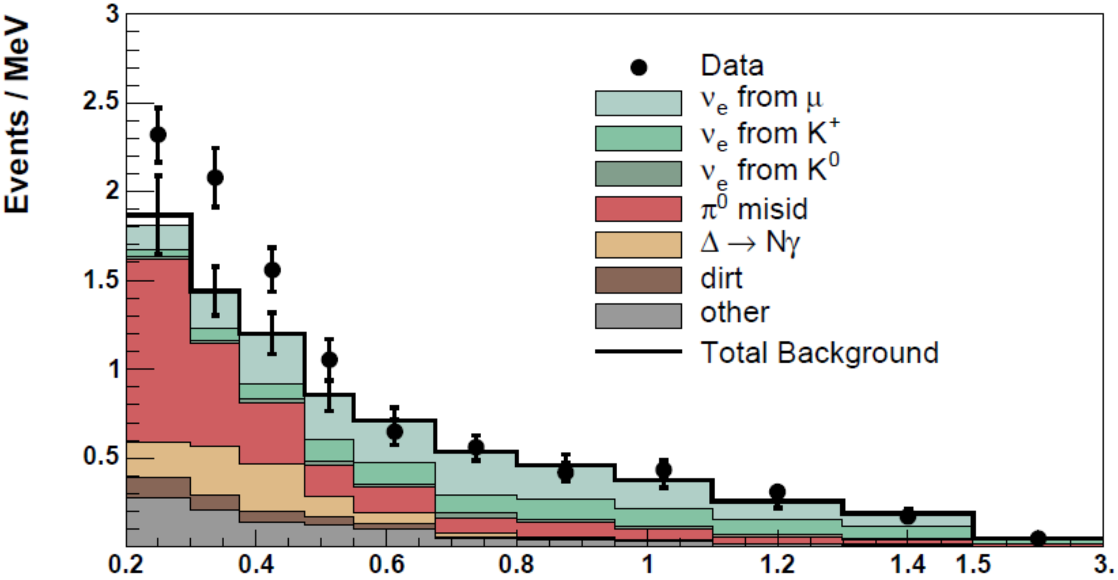
Ankowski et al., PRL 108 (2012), 052505

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

- e-like events in the MiniBooNE $\nu_\mu \to \nu_e$ search:



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

reconstructed ν energy

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

Introduction

- e-like events in the MiniBooNE $\nu_\mu \to \nu_e$ search:

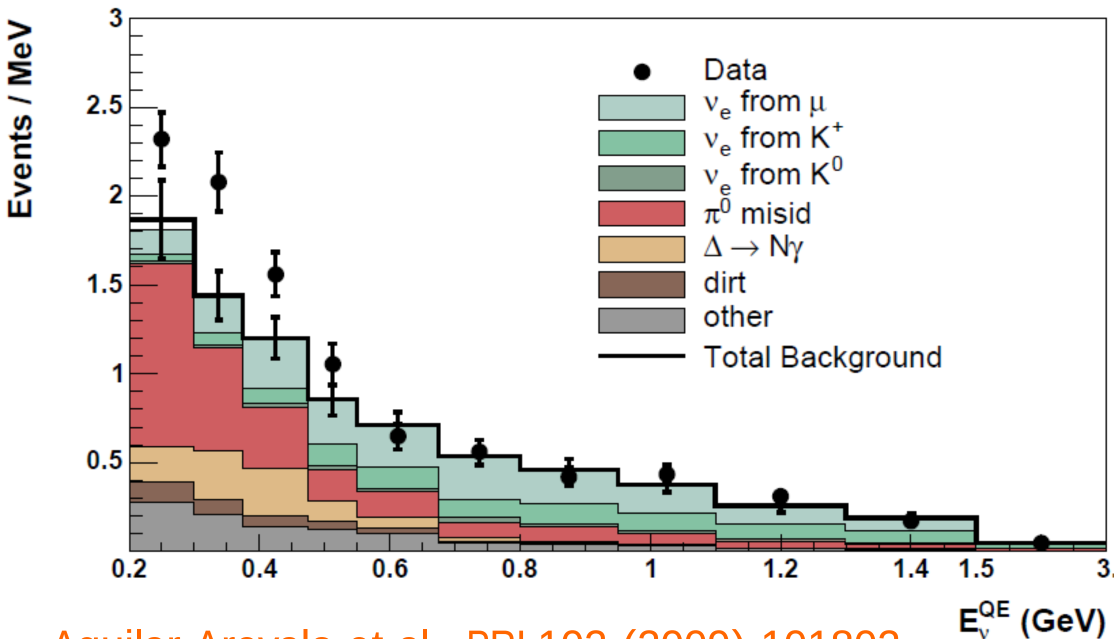


TABLE I. The expected number of events in the $200 < E_\nu^{QE} < 300$ MeV, $300 < E_\nu^{QE} < 475$ MeV, and $475 < E_\nu^{QE} < 1250$ MeV energy ranges from all of the backgrounds after the complete event selection of the final analysis.

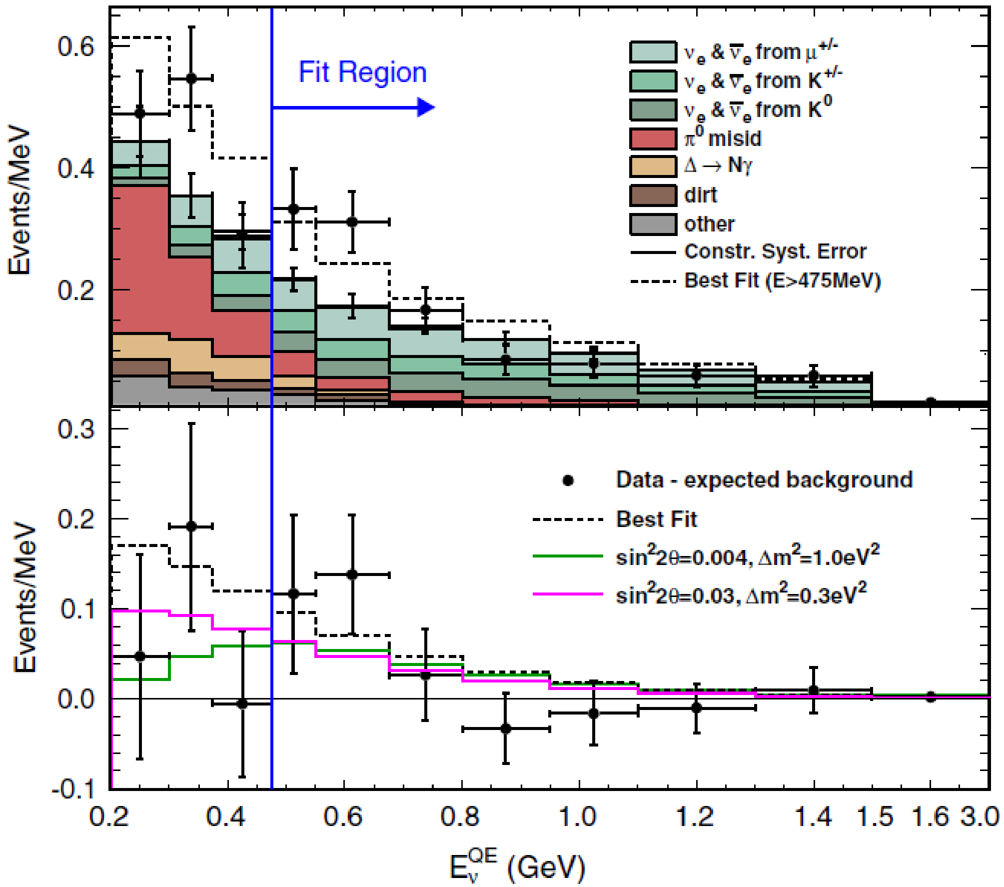
Process	200–300	300–475	475–1250
ν_μ CCQE	9.0	17.4	11.7
$\nu_\mu e \to \nu_\mu e$	6.1	4.3	6.4
NC π^0	103.5	77.8	71.2
NC $\Delta \to N\gamma$	19.5	47.5	19.4
External events	11.5	12.3	11.5
Other events	18.4	7.3	16.8
ν_e from μ decay	13.6	44.5	153.5
ν_e from K^+ decay	3.6	13.8	81.9
ν_e from K_L^0 decay	1.6	3.4	13.5
Total background	186.8 ± 26.0	228.3 ± 24.5	385.9 ± 35.7

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

- Unexplained excess of events at 200 < E_ν^{QE} < 475 MeV
  - NC π^o production ← largest background
  - NC $\Delta \to N \gamma$ ← 2nd largest background: determined from the number of measured NC π^o events
  - Shape of event excess consistent with NC π^o & NC $\Delta \to N \gamma$

Introduction

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



Aguilar-Arevalo et al., PRL105 (2010) 181801

- Excess of events at E_ν^{QE} > 475 MeV consistent with LSND
- Excess of events at 200 < E_ν^{QE} < 475 MeV absent only if oscillations are considered

Introduction

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

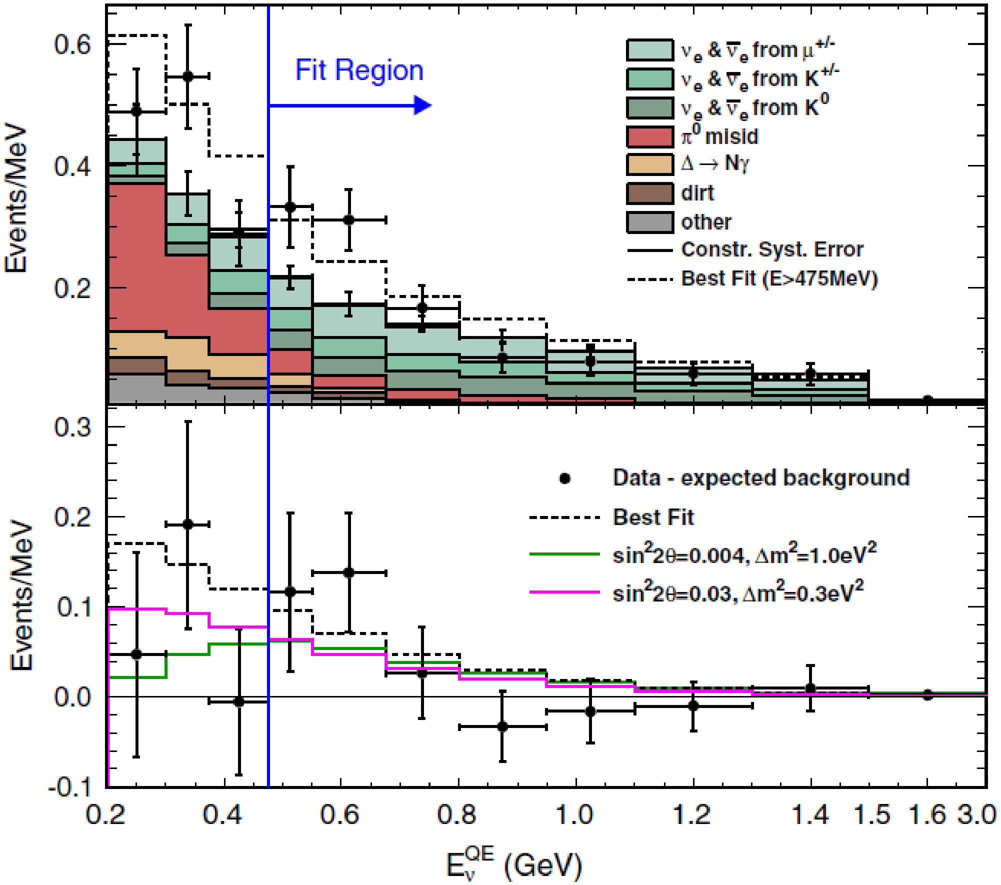


TABLE I. The expected (unconstrained) number of events for different E_ν^{QE} ranges from all of the backgrounds in the $\bar{\nu}_e$ appearance analysis and for the LSND expectation (0.26% oscillation probability averaged over neutrino energy) of $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, for 5.66×10^{20} POT.

Process	200–475 MeV	475–1250 MeV
ν_μ & $\bar{\nu}_\mu$ CCQE	4.3	2.0
NC π^0	41.6	12.6
NC $\Delta \to N\gamma$	12.4	3.4
External events	6.2	2.6
Other ν_μ & $\bar{\nu}_\mu$	7.1	4.2
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ decay	13.5	31.4
ν_e & $\bar{\nu}_e$ from $K^\pm$ decay	8.2	18.6
ν_e & $\bar{\nu}_e$ from K_L^0 decay	5.1	21.2
Other ν_e & $\bar{\nu}_e$	1.3	2.1
Total background	99.5	98.1
0.26% $\bar{\nu}_\mu \to \bar{\nu}_e$	9.1	29.1

Aguilar-Arevalo et al., PRL105 (2010) 181801

- At 200 < E_ν^{QE} < 475 MeV
  - NC π^0 production ← largest background
  - NC $\Delta \to N \gamma$ ← 3rd largest background

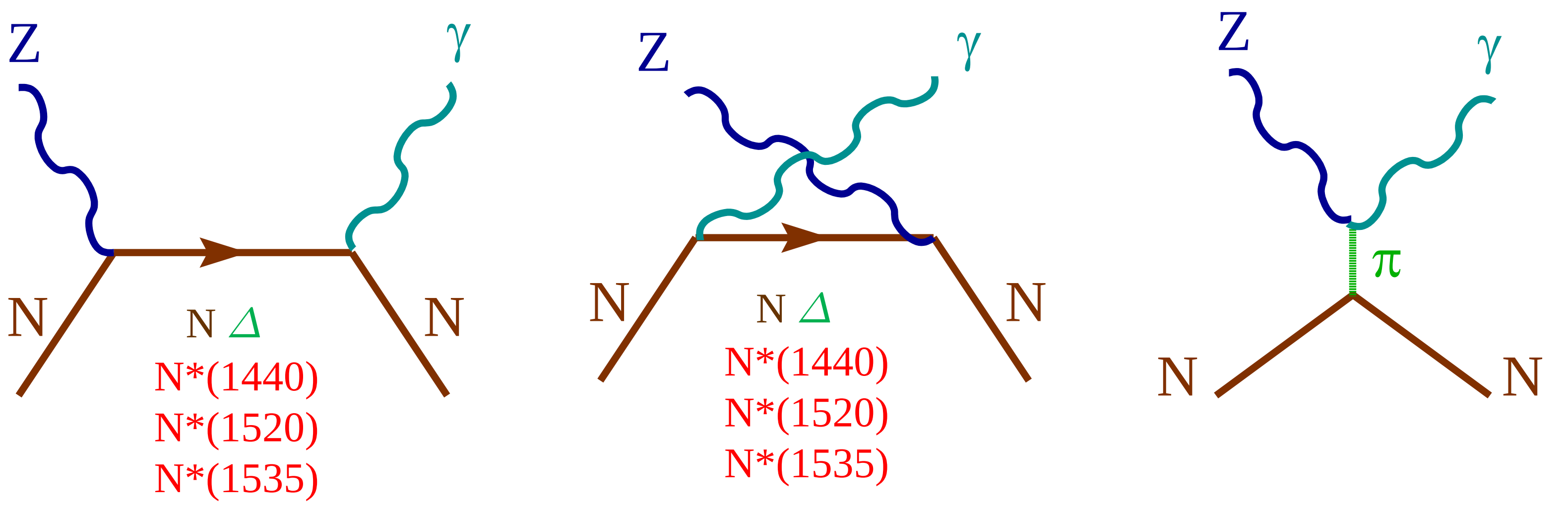
Introduction

- Models:
  - R. Hill, PRD 81 (2010); 84 (2011)
  - Hadronic degrees of freedom N, $\Delta(1232)$, π, ρ, ω
  - EFTh consistent with the SM symmetries at low energy
  - Extrapolation to E_ν ~1-2 GeV using phenomenological form factors
  - Applied to MiniBooNE e-like events but without nuclear corrections

  - Zhang & Serot, PRC 86 (2012) 015501, 035502, 035504
  - EFTh on nucleons
  - Includes N, $\Delta(1232)$, π but also higher orders/heavy meson fields at tree level (no loops)
  - Applied to incoherent and coherent reactions on nuclei
  - Extended to higher energies using form factors to study MiniBooNE excess of events, PLB 719 (2013)

The model

- Feynman diagrams:



The model

- Amplitude:

$$\mathcal{M}_r = \frac{G_F\, e}{\sqrt{2}}\, \epsilon_\mu^{*(r)} \bar{u}(p')\Gamma^{\mu\alpha} u(p) l_\alpha$$

G_F $\leftarrow$ Fermi constant

e $\leftarrow$ electric charge

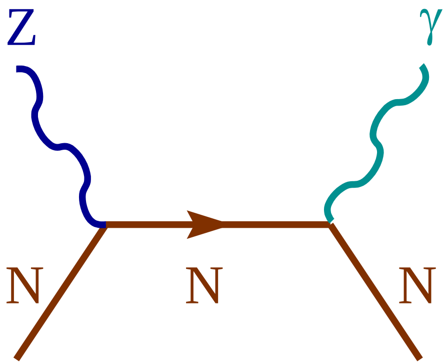
$\epsilon_\mu^{*(r)}$ $\leftarrow$ photon polarization

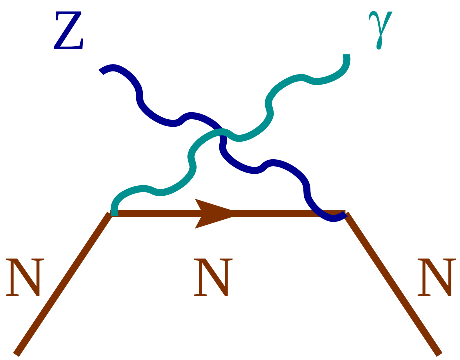
l_α $\leftarrow$ NC for ν or $\bar{\nu}$

$\Gamma^{\mu\alpha}$ $\leftarrow$ specific for each mechanism

The model

- Nucleon pole terms:





$$\Gamma^{\mu\alpha} = J^{\mu}_{\mathrm{EM}}(-q_\gamma) D_N(p+q) J^{\alpha}_{\mathrm{NC}}(q) + J^{\alpha}_{\mathrm{NC}}(q) D_N(q_\gamma - p) J^{\mu}_{\mathrm{EM}}(-q_\gamma)$$

q $\leftarrow$ 4-momentum transferred to the nucleon

q_γ $\leftarrow$ photon 4-momentum

$$D_N(p) = \frac{1}{\not p - m_N}$$ $\leftarrow$ nucleon propagator

The model

- Nucleon pole terms:

$$\Gamma^{\mu\alpha} = J^{\mu}_{\rm EM}(-q_\gamma) D_N(p+q) J^{\alpha}_{\rm NC}(q) + J^{\alpha}_{\rm NC}(q) D_N(q_\gamma - p) J^{\mu}_{\rm EM}(-q_\gamma)$$

$$J^{\alpha}_{\rm NC}(q) = \gamma^\alpha \tilde{F}_1(q^2) + \frac{i}{2M}\sigma^{\alpha\beta} q_\beta \tilde{F}_2(q^2) - \gamma^\mu \gamma_5 \tilde{F}_A(q^2)$$

- Vector NC form factors:

$$2\tilde{F}^{(p)}_{1,2} = (1 - 4\sin^2\theta_W) F^{(p)}_{1,2} - F^{(n)}_{1,2} - F^{(s)}_{1,2}$$
$$2\tilde{F}^{(n)}_{1,2} = (1 - 4\sin^2\theta_W) F^{(n)}_{1,2} - F^{(p)}_{1,2} - F^{(s)}_{1,2}$$

  - $F^{(p,n)}_{1,2}$ $\leftarrow$ p,n EM form factors (dipole parametrizations)
  - $F^{(s)}_{1,2}$ $\leftarrow$ strange EM form factors $\rightarrow$ 0

The model

- Nucleon pole terms:

$$\Gamma^{\mu\alpha} = J^{\mu}_{\rm EM}(-q_\gamma) D_N(p+q) J^{\alpha}_{\rm NC}(q) + J^{\alpha}_{\rm NC}(q) D_N(q_\gamma - p) J^{\mu}_{\rm EM}(-q_\gamma)$$

$$J^{\alpha}_{\rm NC}(q) = \gamma^\alpha \tilde{F}_1(q^2) + \frac{i}{2M}\sigma^{\alpha\beta} q_\beta \tilde{F}_2(q^2) - \gamma^\mu \gamma_5 \tilde{F}_A(q^2)$$

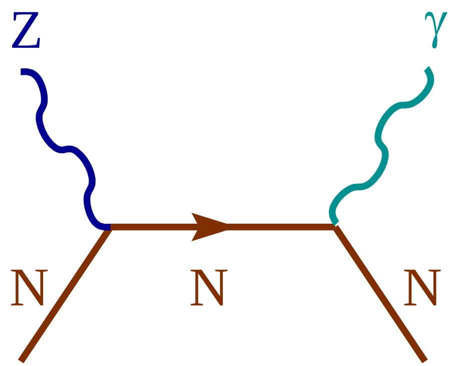
- Axial NC form factor:

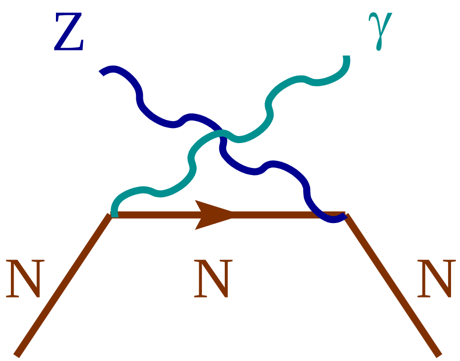
$$2\tilde{F}_A^{(p,n)} = \pm F_A + F_A^{(s)} \quad F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

  - $g_A = 1.267$, $M_A = 1.016$ GeV
  - $F_A^{(s)}$ $\leftarrow$ strange axial form factors $\rightarrow$ 0

The model

- Nucleon pole terms:





$$\Gamma^{\mu\alpha} = J^{\mu}_{\mathrm{EM}}(-q_\gamma) D_N(p+q) J^{\alpha}_{\mathrm{NC}}(q) + J^{\alpha}_{\mathrm{NC}}(q) D_N(q_\gamma - p) J^{\mu}_{\mathrm{EM}}(-q_\gamma)$$

$$J^{\alpha}_{\mathrm{NC}}(q) = \gamma^\alpha \tilde{F}_1(q^2) + \frac{i}{2M}\sigma^{\alpha\beta} q_\beta \tilde{F}_2(q^2) - \gamma^\mu \gamma_5 \tilde{F}_A(q^2)$$

$$J^{\mu}_{\mathrm{EM}}(-q_\gamma) = \gamma^\mu F_1^{(i)}(0) - \frac{i}{2M}\sigma^{\mu\nu} q_{\gamma\,\nu} F_2^{(i)}(0)$$

i = p,n

The model

- $\Delta(1232)$ pole terms:

$$\Gamma^{\mu\alpha} = \hat{J}^{\delta\mu}_{\mathrm{EM}}(p', q_\gamma) D^{\Delta}_{\delta\sigma}(p+q) J^{\sigma\alpha}_{\mathrm{NC}}(p,q) + \hat{J}^{\delta\alpha}_{\mathrm{NC}}(p', -q) D^{\Delta}_{\delta\sigma}(q_\gamma - p) J^{\sigma\mu}_{\mathrm{EM}}(p', -q_\gamma)$$

$$\hat{J}^{\alpha\beta} = \gamma_0 (J^{\alpha\beta})^\dagger \gamma_0$$

$$D^{\Delta}_{\delta\sigma}(p) = \frac{\Lambda_{\delta\sigma}}{p^2 - m_\Delta^2 + i m_\Delta \Gamma_\Delta(p^2)}$$ ← Delta propagator

$$\Lambda_{\delta\sigma}$$ ← N-Δ projector

$$\Gamma_\Delta(p^2)$$ ← E-dependent width

The model

- $\Delta(1232)$ pole terms:

$$\Gamma^{\mu\alpha} = \hat{J}^{\delta\mu}_{\mathrm{EM}}(p', q_\gamma) D^{\Delta}_{\delta\sigma}(p+q) J^{\sigma\alpha}_{\mathrm{NC}}(p,q) + \hat{J}^{\delta\alpha}_{\mathrm{NC}}(p', -q) D^{\Delta}_{\delta\sigma}(q_\gamma - p) J^{\sigma\mu}_{\mathrm{EM}}(p', -q_\gamma)$$

$$J^{\beta\mu}_{\mathrm{NC}}(p,q) = \left[\frac{\tilde{C}^V_3(q^2)}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{\tilde{C}^V_4(q^2)}{M^2}(g^{\beta\mu} q\cdot p_\Delta - q^\beta p^\mu_\Delta) + \frac{\tilde{C}^V_5(q^2)}{M^2}(g^{\beta\mu} q\cdot p - q^\beta p^\mu) \right]\gamma_5$$
$$+ \frac{\tilde{C}^A_3(q^2)}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{\tilde{C}^A_4(q^2)}{M^2}(g^{\beta\mu} q\cdot p_\Delta - q^\beta p^\mu_\Delta) + \tilde{C}^A_5(q^2) g^{\beta\mu}$$

$$J^{\beta\mu}_{\mathrm{EM}}(p,q_\gamma) = \left[\frac{C^{(p,n)}_3(0)}{M}(g^{\beta\mu}\not{q}_\gamma - q^\beta_\gamma\gamma^\mu) + \frac{C^{(p,n)}_4(0)}{M^2}(g^{\beta\mu} q_\gamma\cdot p_\Delta - q^\beta_\gamma p^\mu_\Delta) + \frac{C^{(p,n)}_5(0)}{M^2}(g^{\beta\mu} q_\gamma\cdot p - q^\beta_\gamma p^\mu) \right]\gamma_5$$

$$\tilde{C}^V_i = -(1 - 2\sin^2\theta_W) C^V_i \qquad C^{(p,n)}_i = -C^V_i$$

$$\tilde{C}^A_i = -C^A_i$$

The model

- $\Delta(1232)$ pole terms:

- N-Δ Vector form factors C_i^V can be obtained from helicity amplitudes extracted from π photo- and electro-production

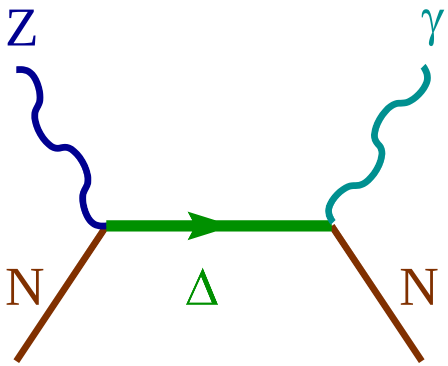
$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^+ J_{\rm EM}^\mu \right| N, J_z = -1/2 \right\rangle \zeta$$

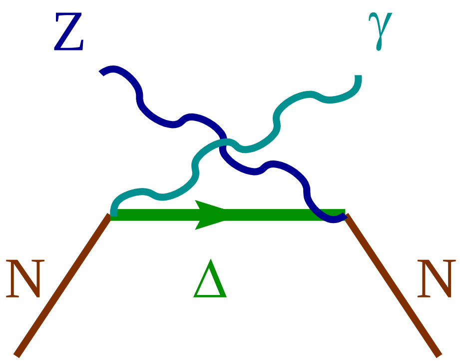
$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 3/2 \left| \epsilon_\mu^+ J_{\rm EM}^\mu \right| N, J_z = 1/2 \right\rangle \zeta$$

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

The model

- $\Delta(1232)$ pole terms:





- N-Δ Axial form factors C_i^A

$$C_4^A = -\frac{1}{4} C_5^A \qquad C_3^A = 0 \leftarrow \text{Adler model}$$

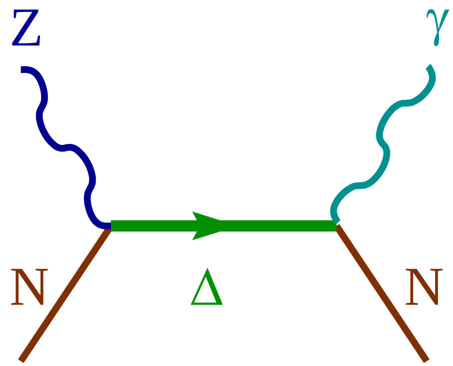
$$C_5^A = C_5^A(0) \left(1 + \frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$$

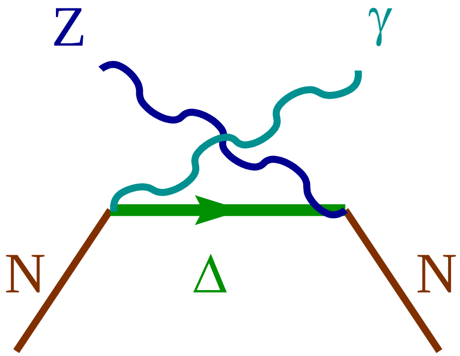
  - $C^A_5(0)$ =1.00 ± 0.11, $M_{A\,\Delta}$ = 0.93 ± 0.07 GeV

    Hernandez et al., PRD 81 (2010)

The model

- N* pole terms:





- N-N* Vector form factors can be obtained from helicity amplitudes

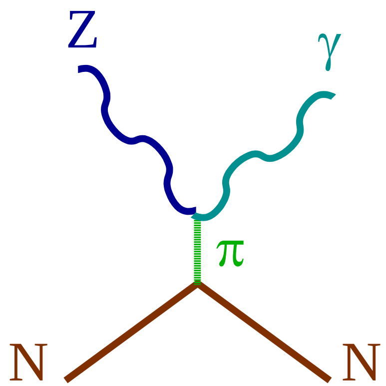
- N-N* Axial form factors:
  - PCAC $q^\alpha A_\alpha \approx 0$
  - π-pole dominance of the pseudoscalar form factor: $F_P,\ C_6^A$
  - Dipole q^2 dependence

$$F_A, C_5^A(q^2) = F_A, C_5^A(0)\left(1 - \frac{q^2}{{M_A}^2}\right)^{-2}$$

$$M_A = 1\ \mathrm{GeV}$$

The model

- π pole term:



  - from the anomalous part of the Lagrangian

$$\Gamma^{\mu\alpha} = -i c_{p,n} \frac{g_A m_N}{4\pi^2 f_\pi^2} \left(\frac{1}{2} - 2\sin^2\theta_W \right) \epsilon^{\sigma\delta\mu\alpha} q_{\gamma\,\sigma} q_\delta \, \gamma_5 D_\pi(p'-p) F_\pi(p'-p)$$

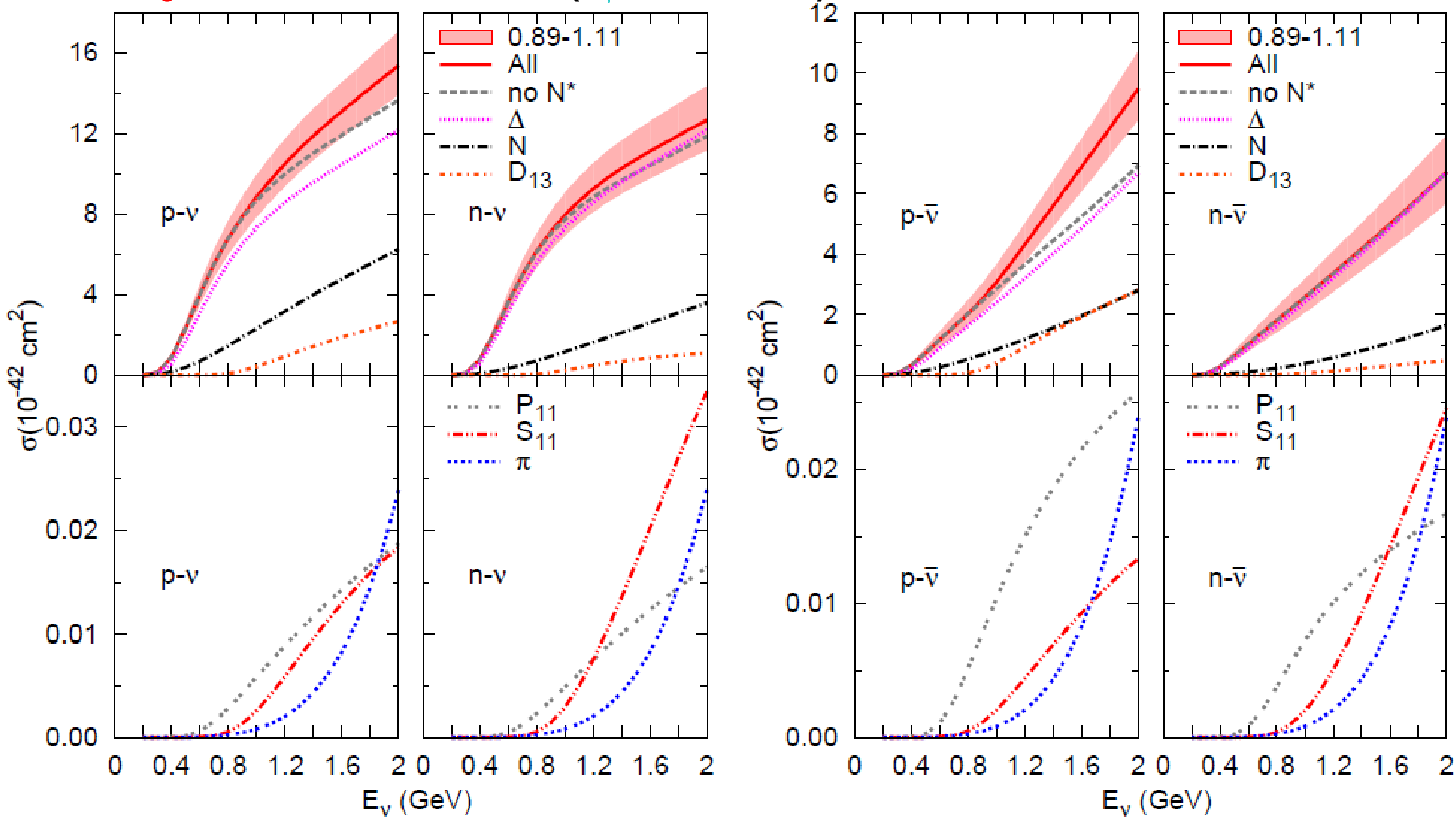
$$D_\pi(p) = \frac{1}{p^2 - m_\pi^2}$$ ← π propagator

$$F_\pi(p) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - p^2}$$ $\Lambda = 1.2$ GeV ← off-shell form factor

$c_{p,n} = \pm 1$

Results on nucleons

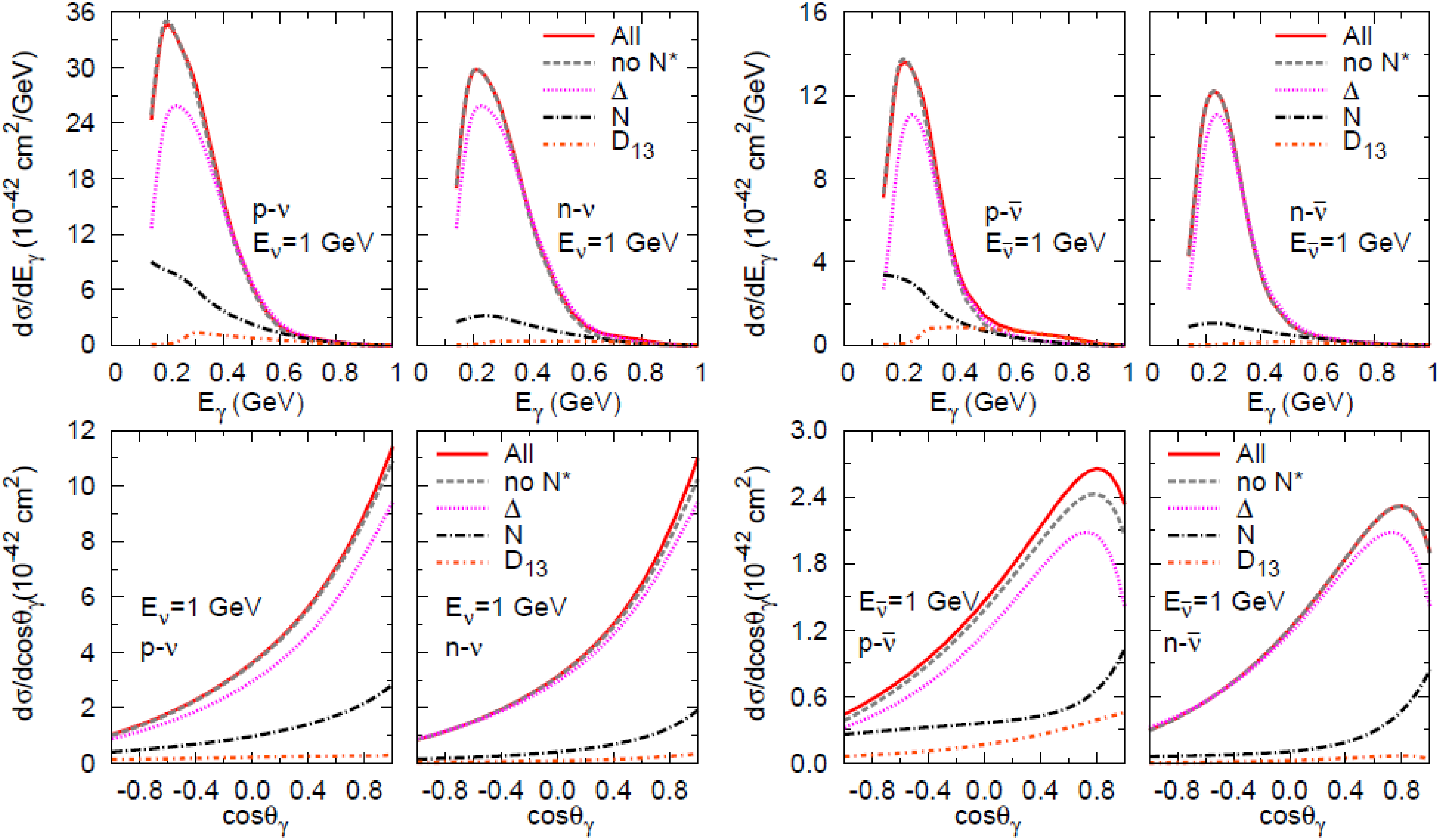
- Integrated cross sections (E_γ > 140 MeV)



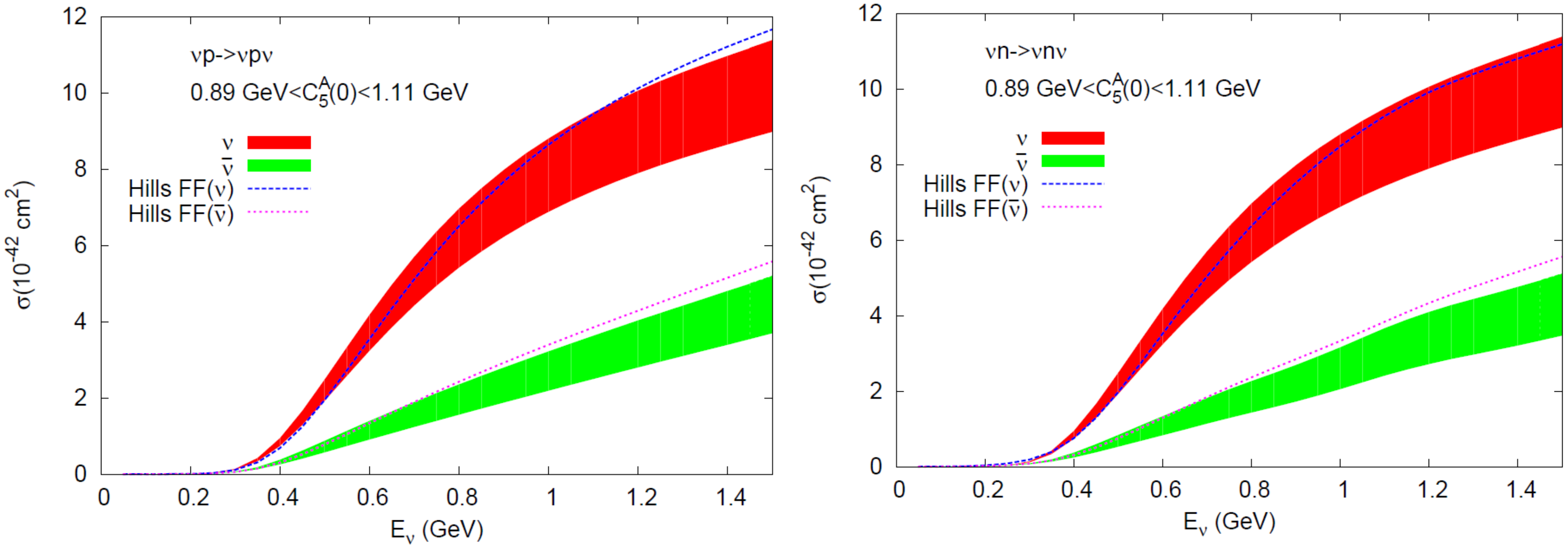
- Error band: $C^A_5(0)$ =1.00 ± 0.11 Hernandez et al., PRD 81 (2010)

Results on nucleons

- Differential cross sections at E_ν = 1 GeV (E_γ > 140 MeV)



Comparison



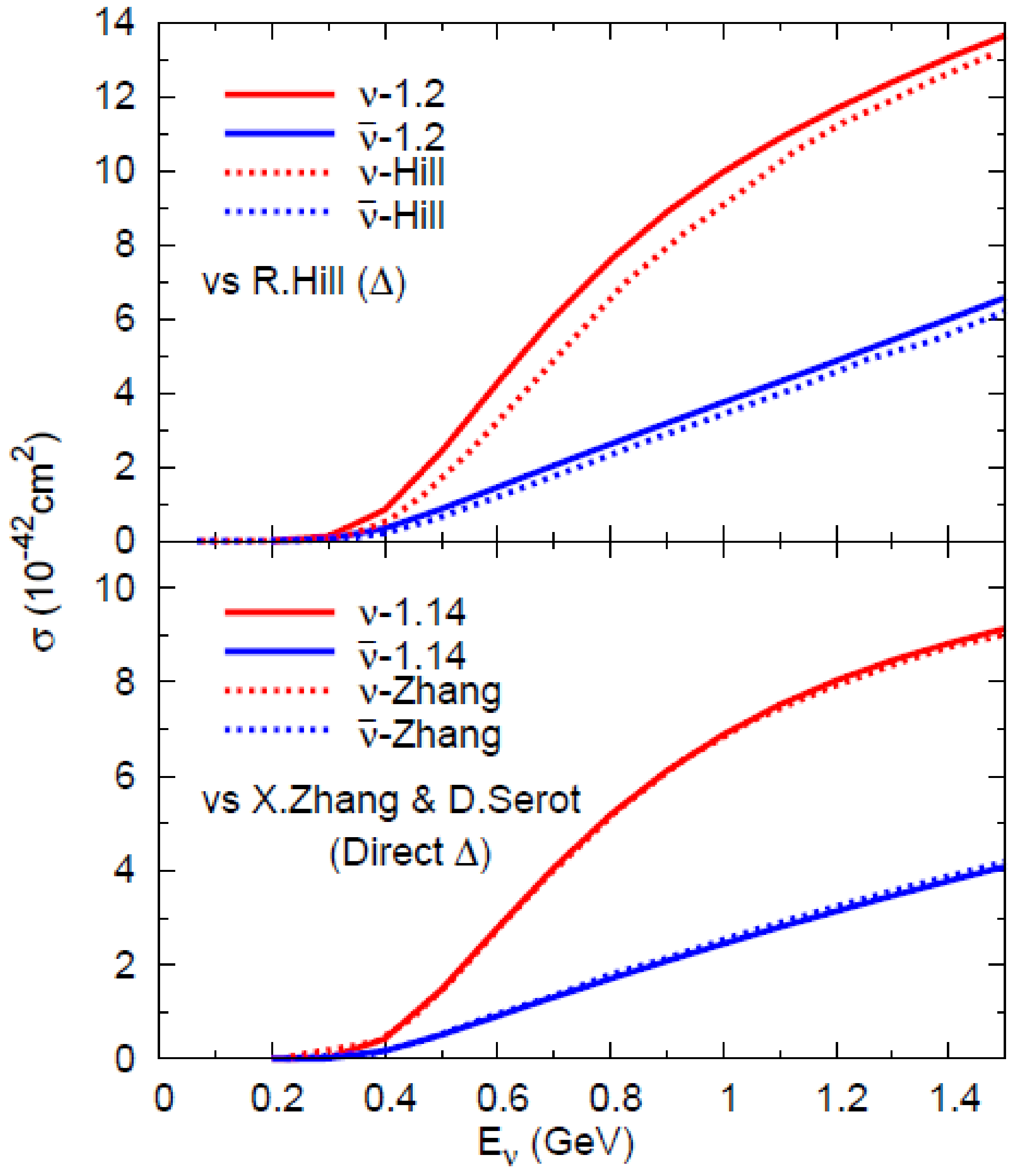
- N+Δ only
- Error band: $C^A_5(0)$ =1.00 ± 0.11 Hernandez et al., PRD 81 (2010)
- Main differences with R. Hill, PRD 81 (2010)
  - $C^A_5(0)$ = 1.00 ± 0.11 GeV vs 1.2
  - Energy dependent Γ_Δ vs Γ_Δ = const = 120 MeV
  - For nucleon pole diags.: M_A = 1 vs 1.2 GeV

Comparison

- Only Δ

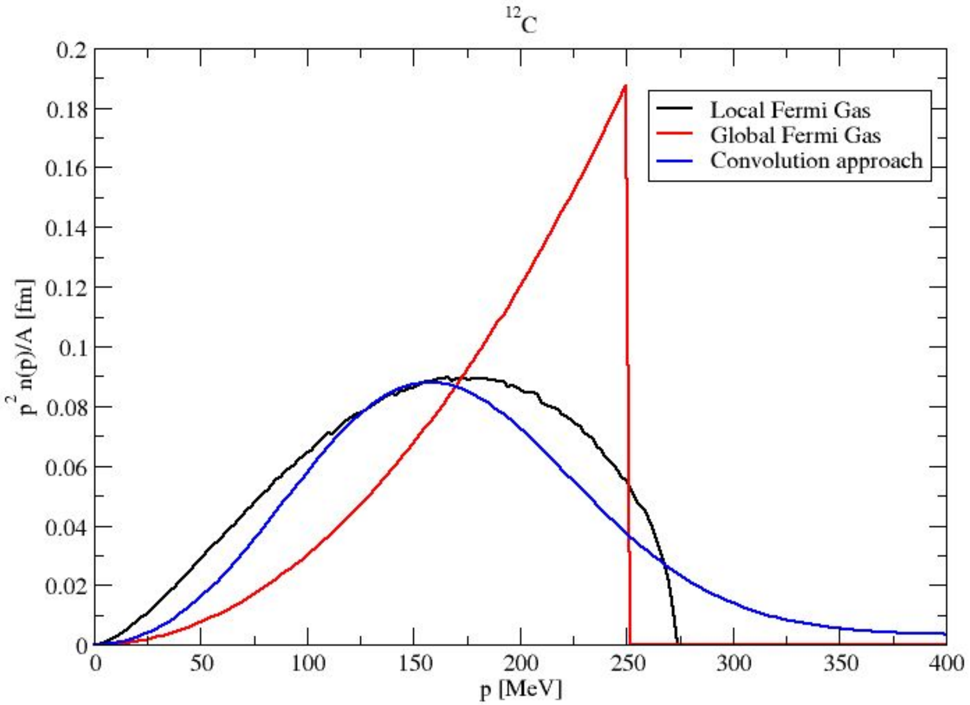
- $C^A_5(0)$ =1.2
- No cut in E_γ

- $C^A_5(0)$ =1.14
- E_γ> 200 MeV



Nuclear effects

- $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, X$
- Relativistic Local Fermi Gas $p_F(r) = [\frac{3}{2}\pi^2\rho(r)]^{1/3}$
- Fermi motion $f(\vec{r},\vec{p}) = \Theta(p_F(r) - |\vec{p}|)$
- Pauli blocking $P_{\text{Pauli}} = 1 - \Theta(p_F(r) - |\vec{p}|)$
- Free nucleons but with space-momentum correlations absent in the GFG



Convolution model:
Ciofi degli Atti, Simula, PRC 53 (1996)

Nuclear effects

- $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$
- In-medium modification of the $\Delta(1232)$ resonance
  - In $\dfrac{1}{p^2 - m_\Delta^2 + i m_\Delta \Gamma_\Delta(p^2)}$

replace
$$M_\Delta \quad \to \quad M_\Delta + \mathrm{Re}\Sigma_\Delta(\rho)$$
$$\frac{\Gamma_\Delta}{2} \quad \to \quad \frac{\tilde{\Gamma}_\Delta(\rho)}{2} - \mathrm{Im}\Sigma_\Delta(\rho)$$

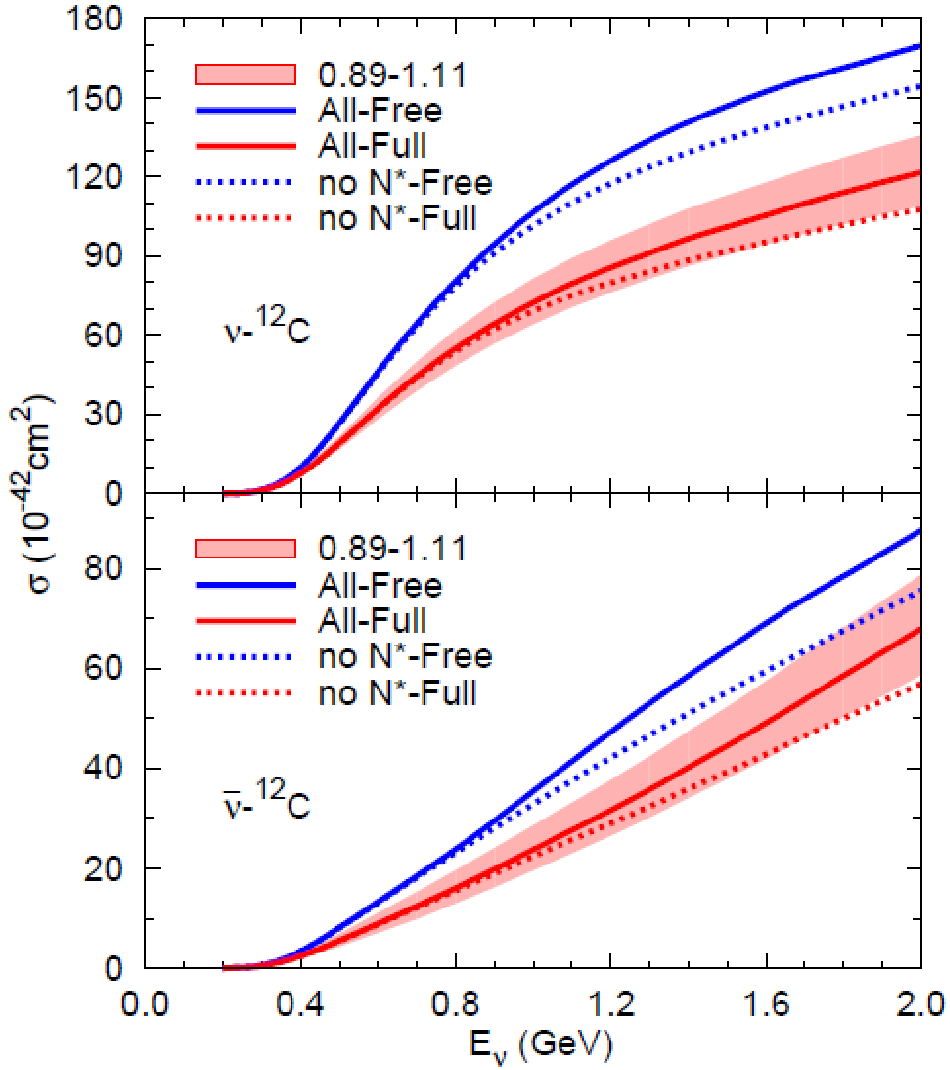
$\tilde{\Gamma}_\Delta \leftarrow$ Free width $\Delta \to N\,\pi$ modified by Pauli blocking

$\mathrm{Re}\Sigma_\Delta(\rho) \approx 0$

$\mathrm{Im}\Sigma_\Delta(\rho) \leftarrow$ many-body processes:
- $\Delta\, N \to N\, N$
- $\Delta\, N \to N\, N\, \pi$
- $\Delta\, N\, N \to N\, N\, N$

Results

- $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$
- Integrated cross section
- $E_\gamma > 140$ MeV
- Error band: $C^A_5(0) = 1.00 \pm 0.11$
- Considerable reduction caused by nuclear effects (~30 %)

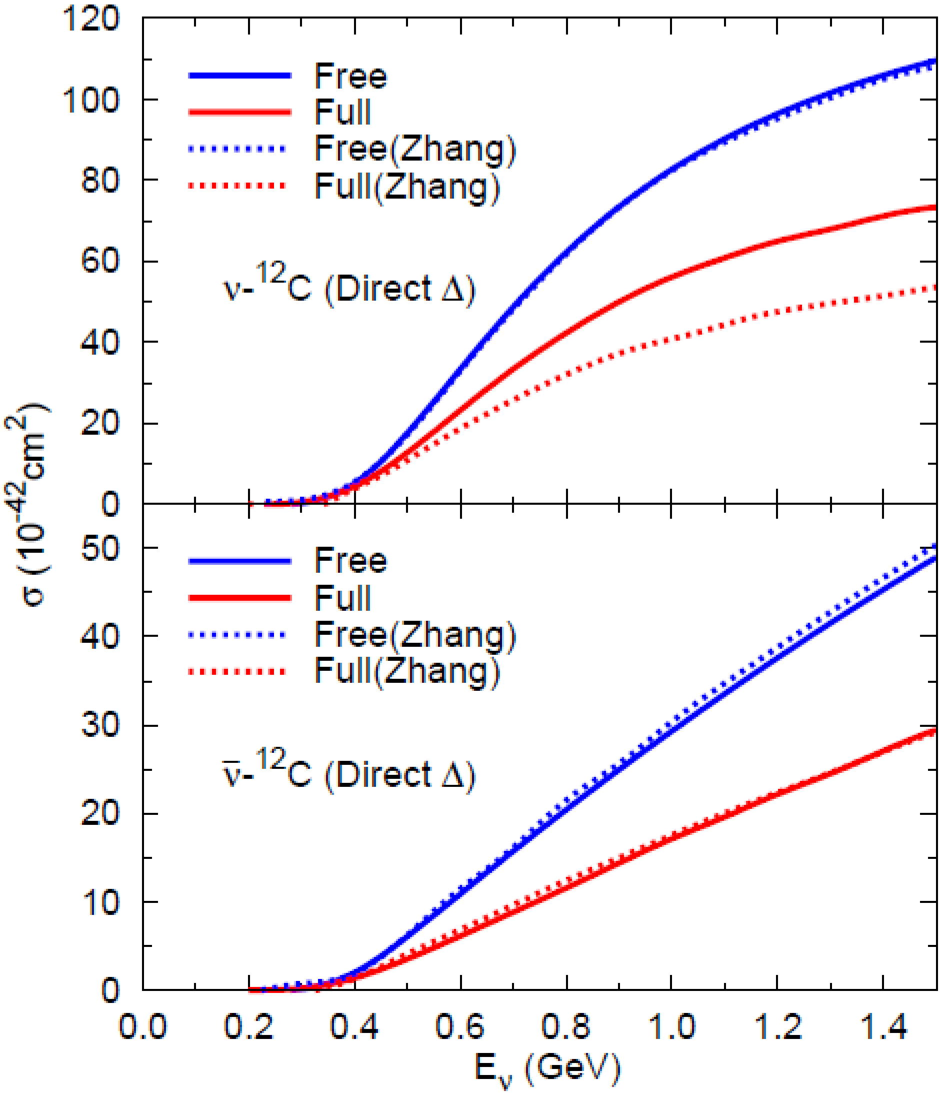


Comparison

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

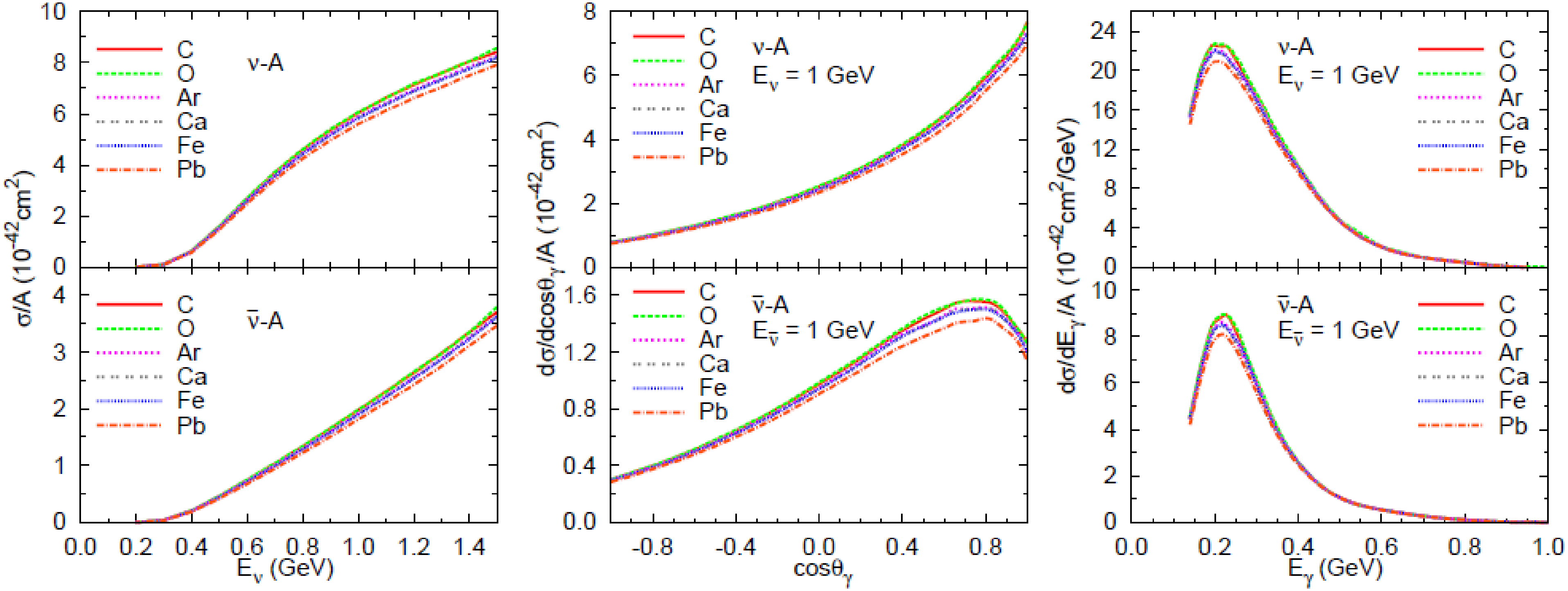
- Integrated cross section

- vs Zhang, Serot, PLB 719 (2013)
- Direct Δ only
- $E_\gamma > 200$ MeV
- $C^A_5(0) = 1.14$



Results

- $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$
- A dependence and differential cross sections at E_ν = 1 GeV
- E_γ> 140 MeV



Coherent NCγ

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

- Microscopic description:
  - Same NCγ mechanisms as in $\nu(\bar{\nu})\, N \to \nu(\bar{\nu})\, \gamma\, N$, $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$
  - Nuclear corrections: $\Gamma_\Delta \to \tilde{\Gamma}_\Delta(\rho) - 2\,\mathrm{Im}\Sigma_\Delta(\rho)$
  - Coherent sum over all nucleons

$$\mathcal{M}_r = \frac{G_F\, e}{\sqrt{2}}\, \epsilon_\mu^{*(r)} \bar{u}(p')\mathcal{A}^{\mu\alpha} u(p) l_\alpha$$

$$\mathcal{A}^{\mu\alpha} = \sum_{r=p,n} \int d\vec{r}\, e^{i(\vec{q}-\vec{q}_\gamma)\cdot\vec{r}} \rho_r(r) \hat{\Gamma}_r^{\mu\alpha}$$

$$\hat{\Gamma}_r^{\mu\alpha} = \frac{1}{2} \sum_i \mathrm{Tr}\left[\bar{u}\, \Gamma^\mu_{i(r)}\, u\right] \quad \leftarrow \text{sum over all mechanisms}$$

Coherent NCγ

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

- Microscopic description:
  - Same NCγ mechanisms as in $\nu(\bar{\nu})\, N \rightarrow \nu(\bar{\nu})\, \gamma\, N$, $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, X$
  - Nuclear corrections: $\Gamma_\Delta \rightarrow \tilde{\Gamma}_\Delta(\rho) - 2\,\mathrm{Im}\Sigma_\Delta(\rho)$
  - Coherent sum over all nucleons

$$\hat{\Gamma}^{\mu\alpha}_r = \frac{1}{2} \sum_i \mathrm{Tr}\left[\bar{u}\,\Gamma^{\mu}_{i(r)}\, u\right] \leftarrow \text{sum over all mechanisms}$$

  - Prescription for nucleon momenta:

$$p = \left(\sqrt{M^2 + \frac{1}{4}\left(\vec{q}_\gamma - \vec{q}\right)^2}, \frac{\vec{q}_\gamma - \vec{q}}{2}\right) \qquad p' = q - q_\gamma + p = \left(\sqrt{M^2 + \frac{1}{4}\left(\vec{q}_\gamma - \vec{q}\right)^2}, -\frac{\vec{q}_\gamma - \vec{q}}{2}\right)$$

    - equally shared by initial and final nucleons
    - similar to the sum over all momenta for Cohπ^o photoproduction Carrasco et al., NPA565 (1993)

Coherent NCγ

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

- Microscopic description:
  - Same NCγ mechanisms as in $\nu(\bar{\nu})\, N \to \nu(\bar{\nu})\, \gamma\, N$
    $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$
  - Nuclear corrections: $\Gamma_\Delta \to \tilde{\Gamma}_\Delta(\rho) - 2\,\mathrm{Im}\Sigma_\Delta(\rho)$
  - Coherent sum over all nucleons

$$\hat{\Gamma}_r^{\mu\alpha} = \frac{1}{2} \sum_i \mathrm{Tr}\left[\bar{u}\, \Gamma^{\mu}_{i(r)}\, u\right] \leftarrow \text{sum over all mechanisms}$$

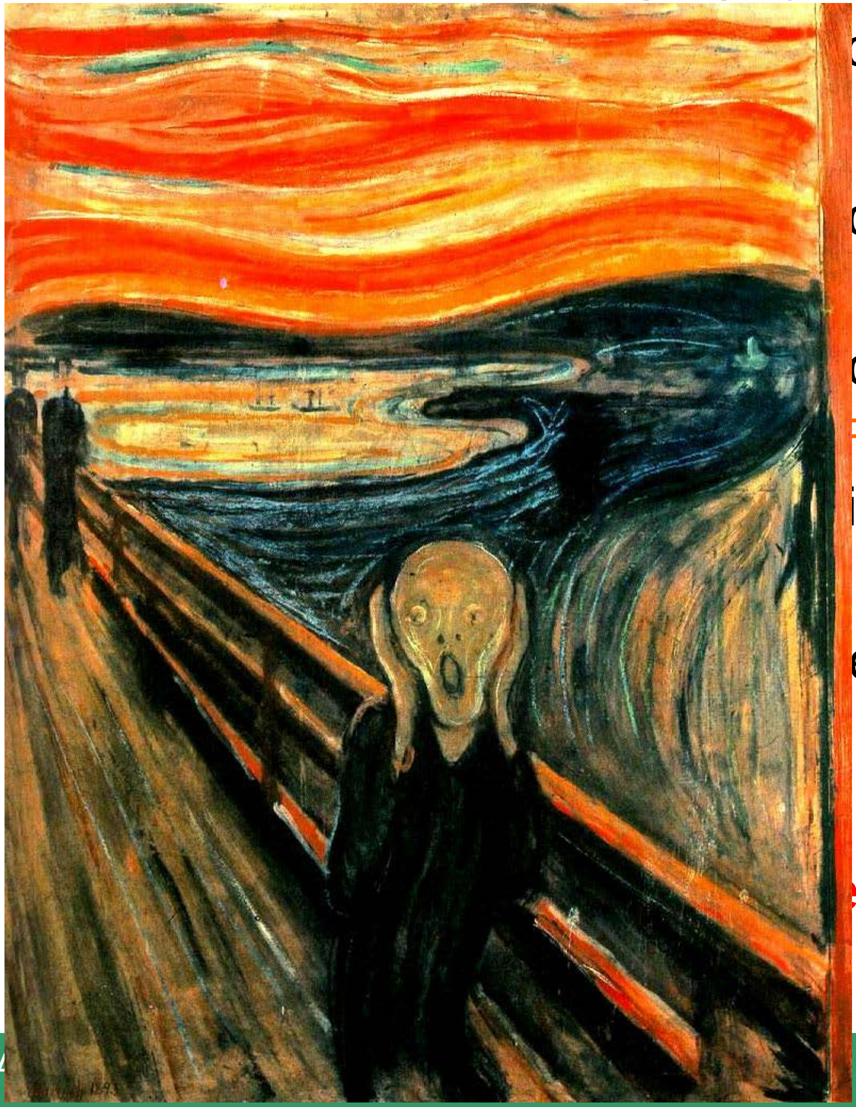
  - Prescription for nucleon momenta:

$$p = \left(\sqrt{M^2 + \frac{1}{4}\left(\vec{q}_\gamma - \vec{q}\right)^2}, \frac{\vec{q}_\gamma - \vec{q}}{2}\right) \qquad p' = q - q_\gamma + p = \left(\sqrt{M^2 + \frac{1}{4}\left(\vec{q}_\gamma - \vec{q}\right)^2}, -\frac{\vec{q}_\gamma - \vec{q}}{2}\right)$$

    - equally shared by initial and final nucleons
    - Δ momentum well defined (local treatment)

Coherent NCγ

- $\nu(\bar{\nu})\,A \rightarrow \nu(\bar{\nu})\,\gamma\,A$
- Non-local treatment of Δ propagation



o the plane wave Cohπ^0 calculation of

- ocal descriptions are a factor 2 off
-

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RC 81 (2010)
ing with the same model

ering

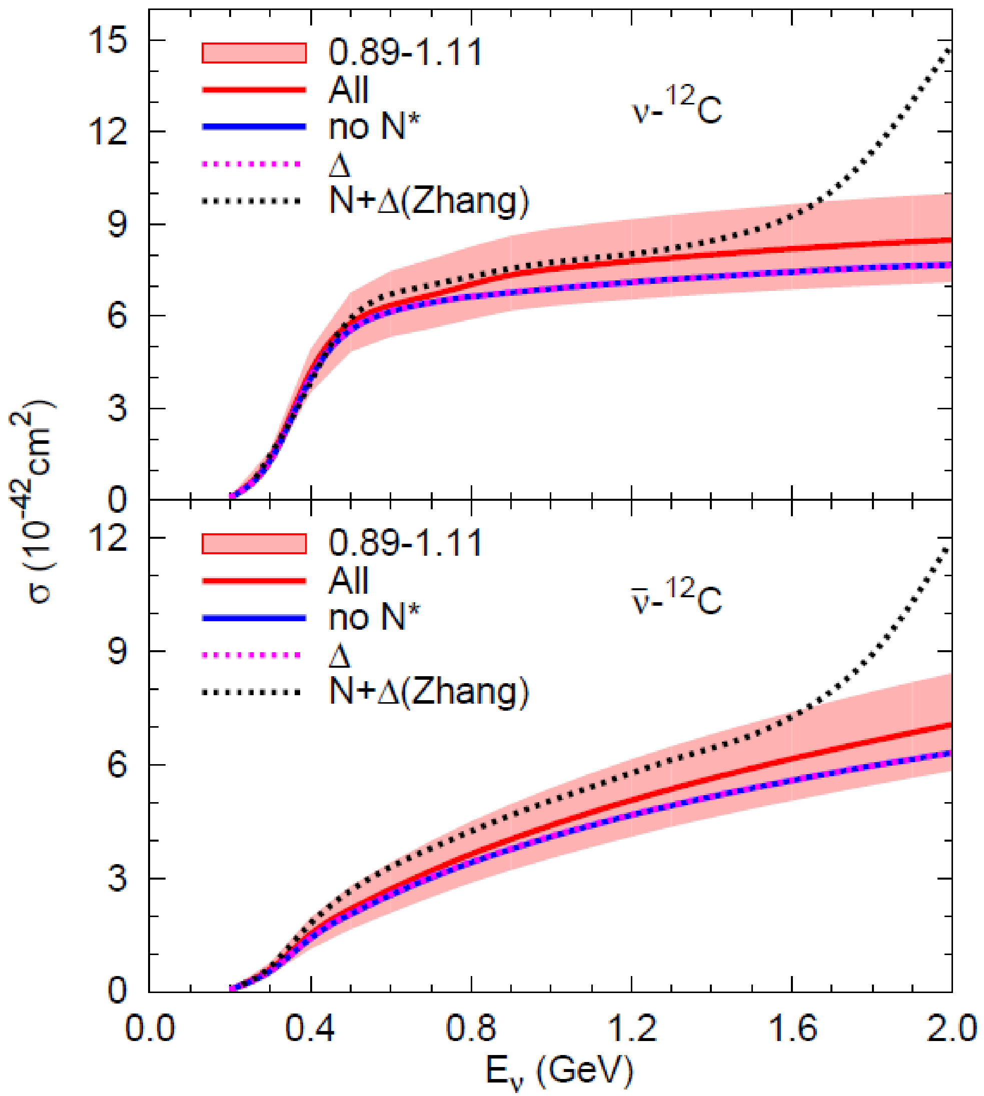
- es πA scattering

Coherent NCγ

- $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, A$
- Non-local treatment of Δ propagation
  - Factor ½ correction according to the plane wave Cohπ^o calculation of Leitner et al., PRC 79 (2009)
- However, this does not prove that local descriptions are a factor 2 off
- In order to (dis)prove this claim:
  - Take a realistic model with nonlocalities and non-local Δ spreading potential (Σ_{spr}) Nakamura et al, PRC 81 (2010)
  - Fit Σ_{spr} parameters to πA scattering with the same model
  - Take the local limit
  - Refit Σ_{spr} parameters to πA scattering
  - Compare results
- Our local approach already describes πA scattering

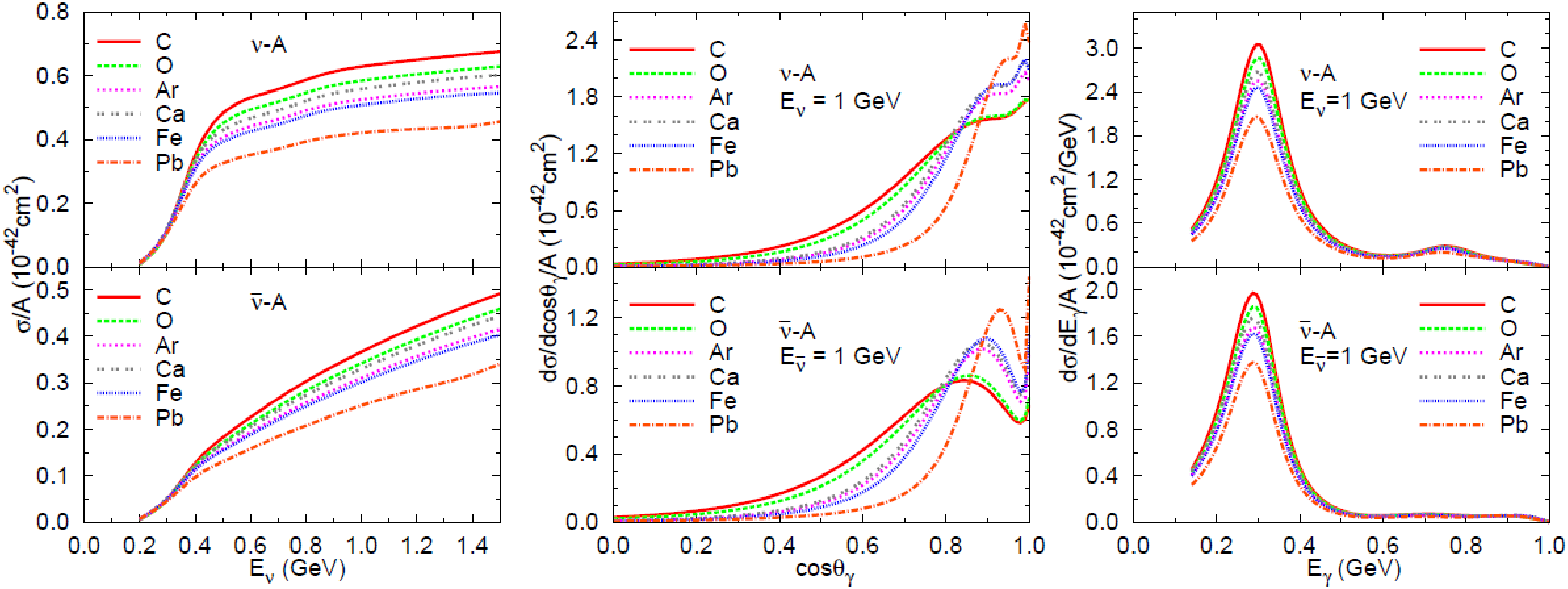
Results and Comparison

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



Results

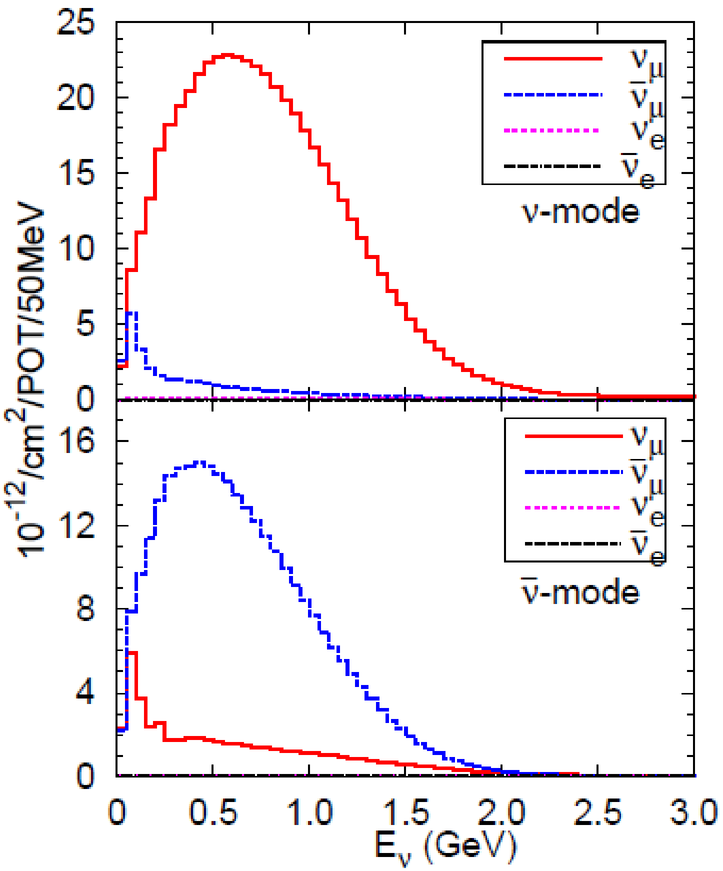
- $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, A$
- A dependence and differential cross sections at E_ν = 1 GeV
- E_γ > 140 MeV



NCγ events at MiniBooNE

- Target: CH_2
- Mass: 806 tons
- POT: 6.46 x 10^{20} (ν mode), 11.27 x 10^{20} ($\bar{\nu}$ mode)
- Fluxes: Aguilar-Arevalo et al, PRD 79 (2009)

Aguilar-Arevalo et al, PRL 110 (2013)



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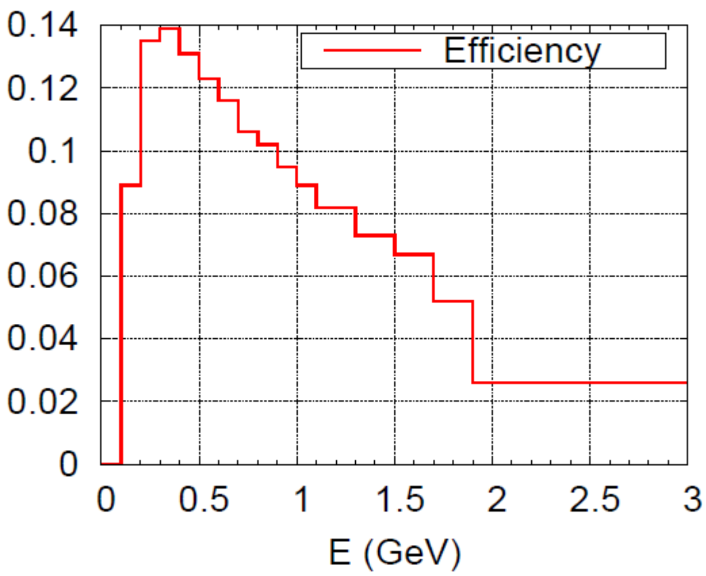
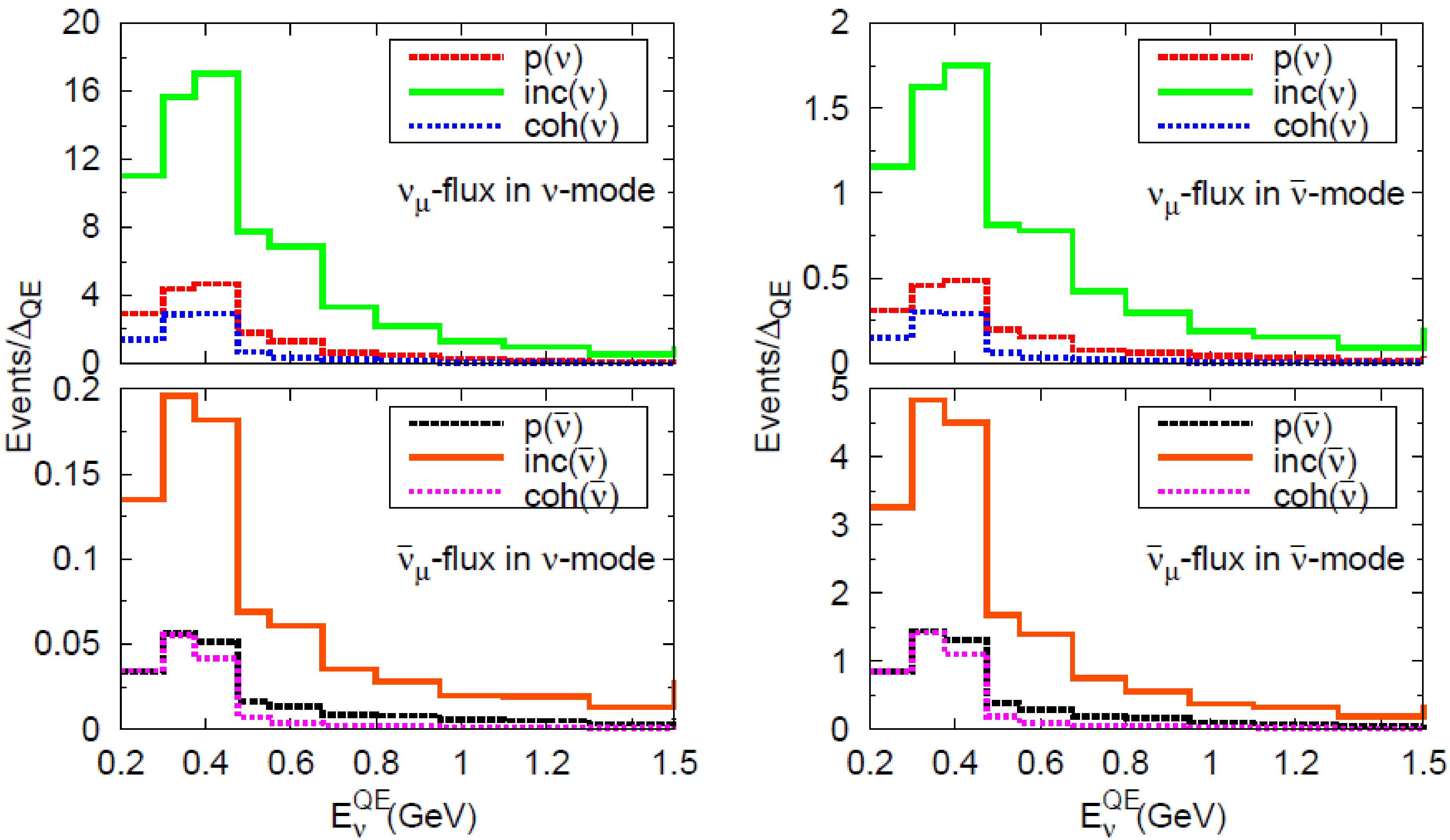
- E_γ detection efficiency:
  http://www-boone.fnal.gov/for physicists/data release/nue_nuebar_2012



NCγ events at MiniBooNE



- 30-40 % of ν induced events in $\bar{\nu}$ mode

NCγ events at MiniBooNE

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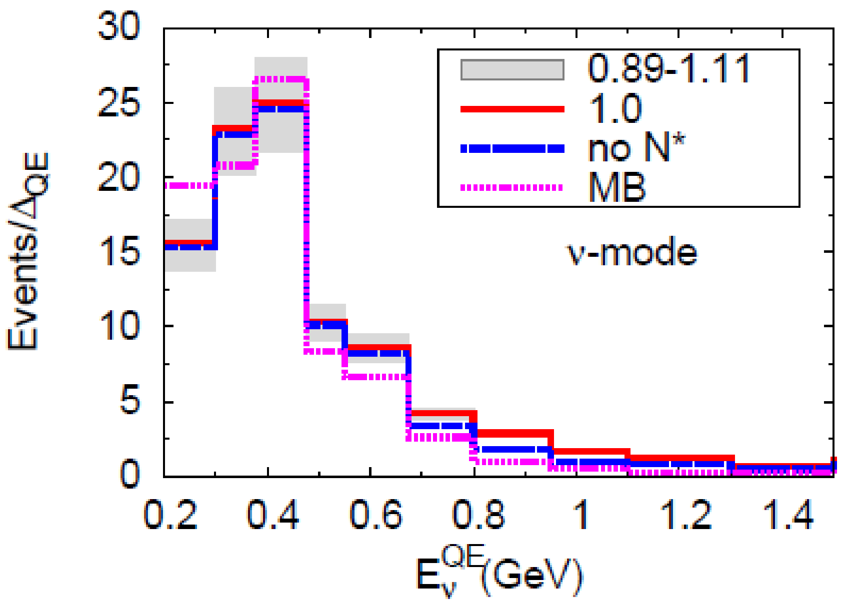

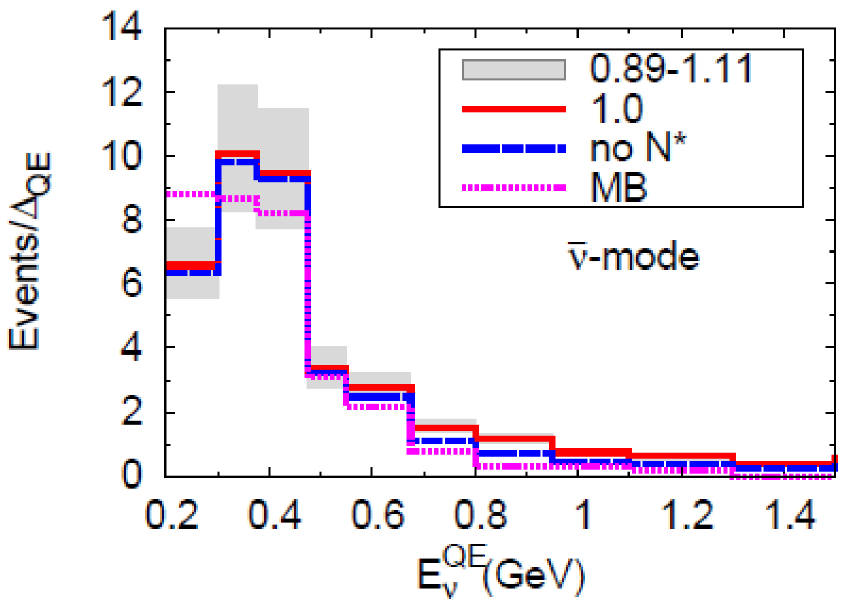

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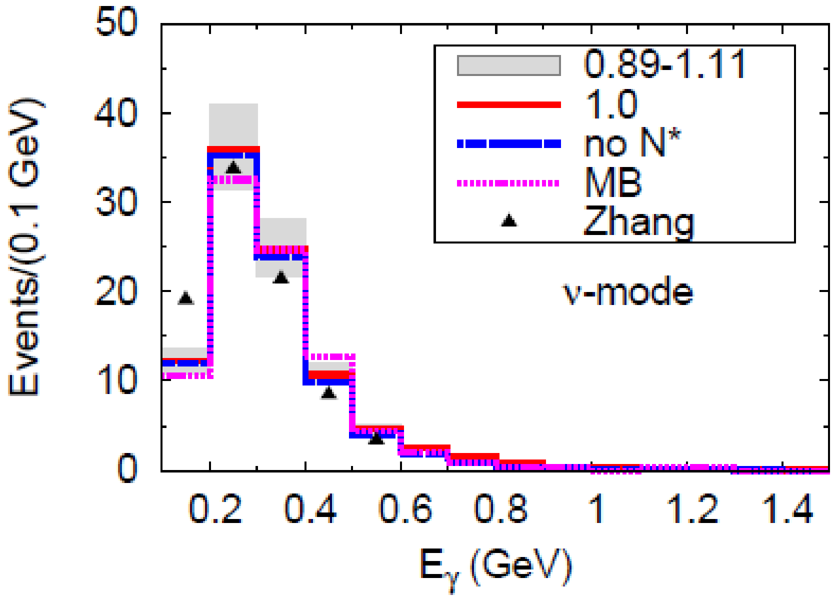
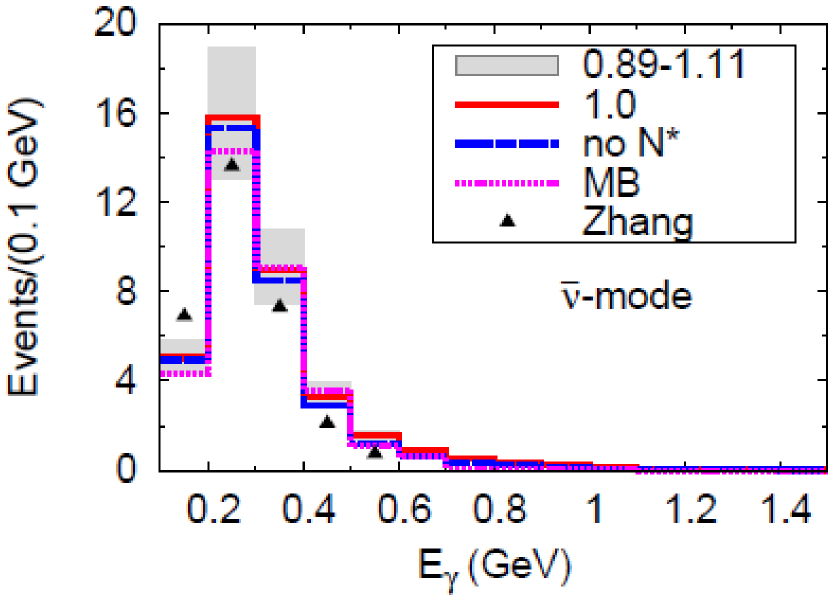
- Comparison to the MiniBooNE estimate and to Zhang, Serot, PLB 719 (2013)





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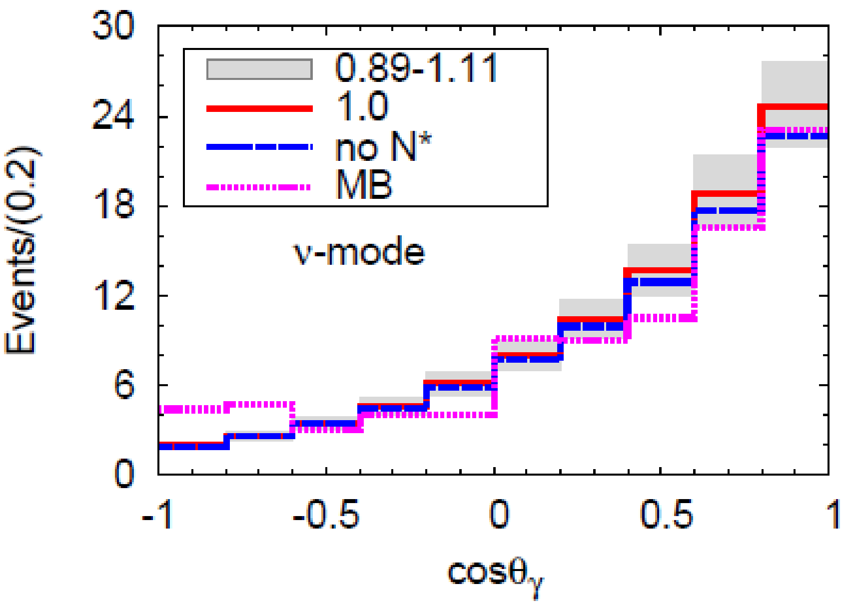
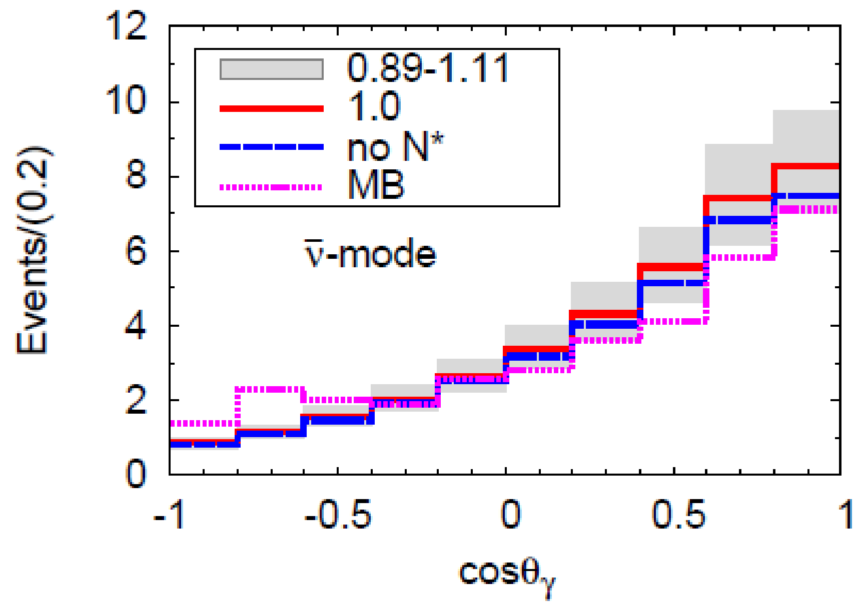


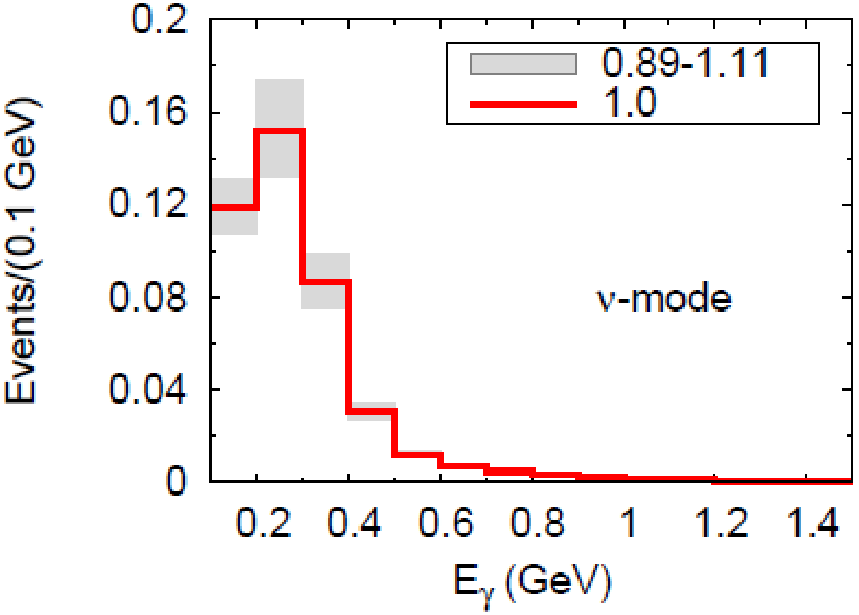


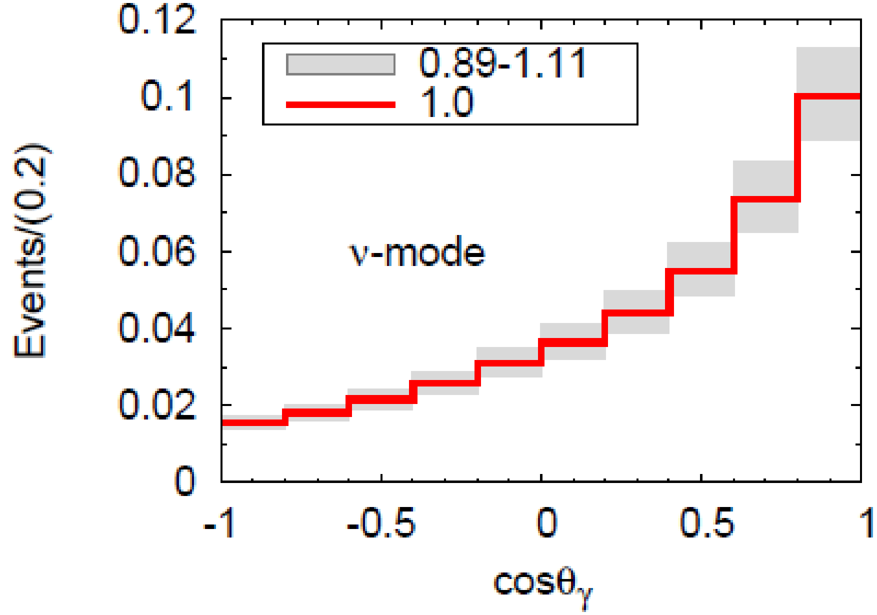
NCγ events at T2K

- Target: H_2O
- Mass: 22.5 ktons
- POT: 6.57 x 10^{20} (ν mode)
- Fluxes: SK250 100 MeV < E_ν < 3 GeV
- No detection efficiency

Abe et al, arXiv:1311.4750

Abe et al, PRD 87 (2013)





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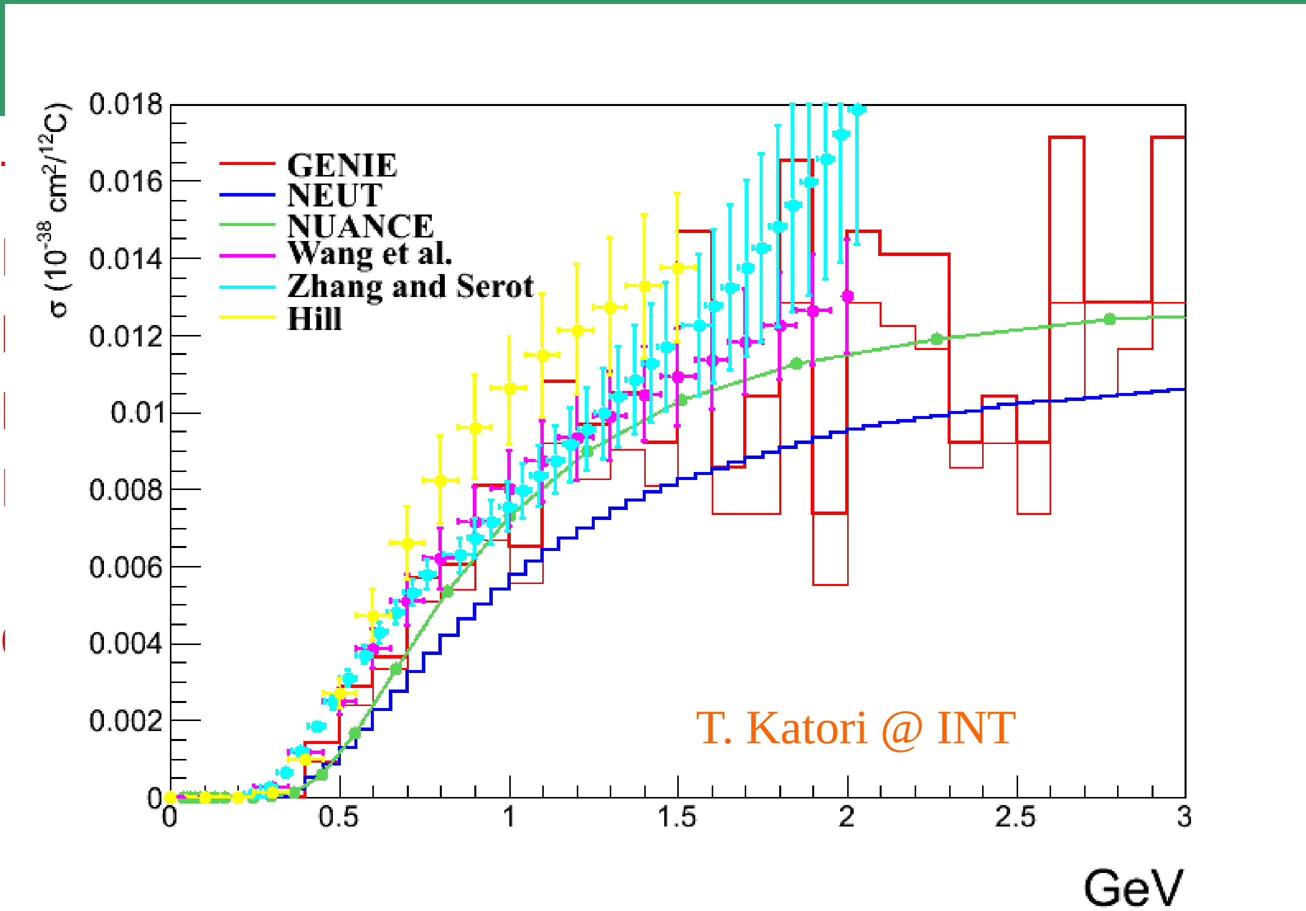
- Comparison to T2K (H. Tanaka, S. Tobayama / NEUT) estimate

	0.89	1.00	1.11	T2K
Events	0.372	0.421	0.475	0.165

- Does this discrepancy come from the NEUT vs Wang et al. cross sections?



(2013)

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NCγ events at T2K

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	0.89	1.00	1.11	T2K
Events	0.372	0.421	0.475	0.165

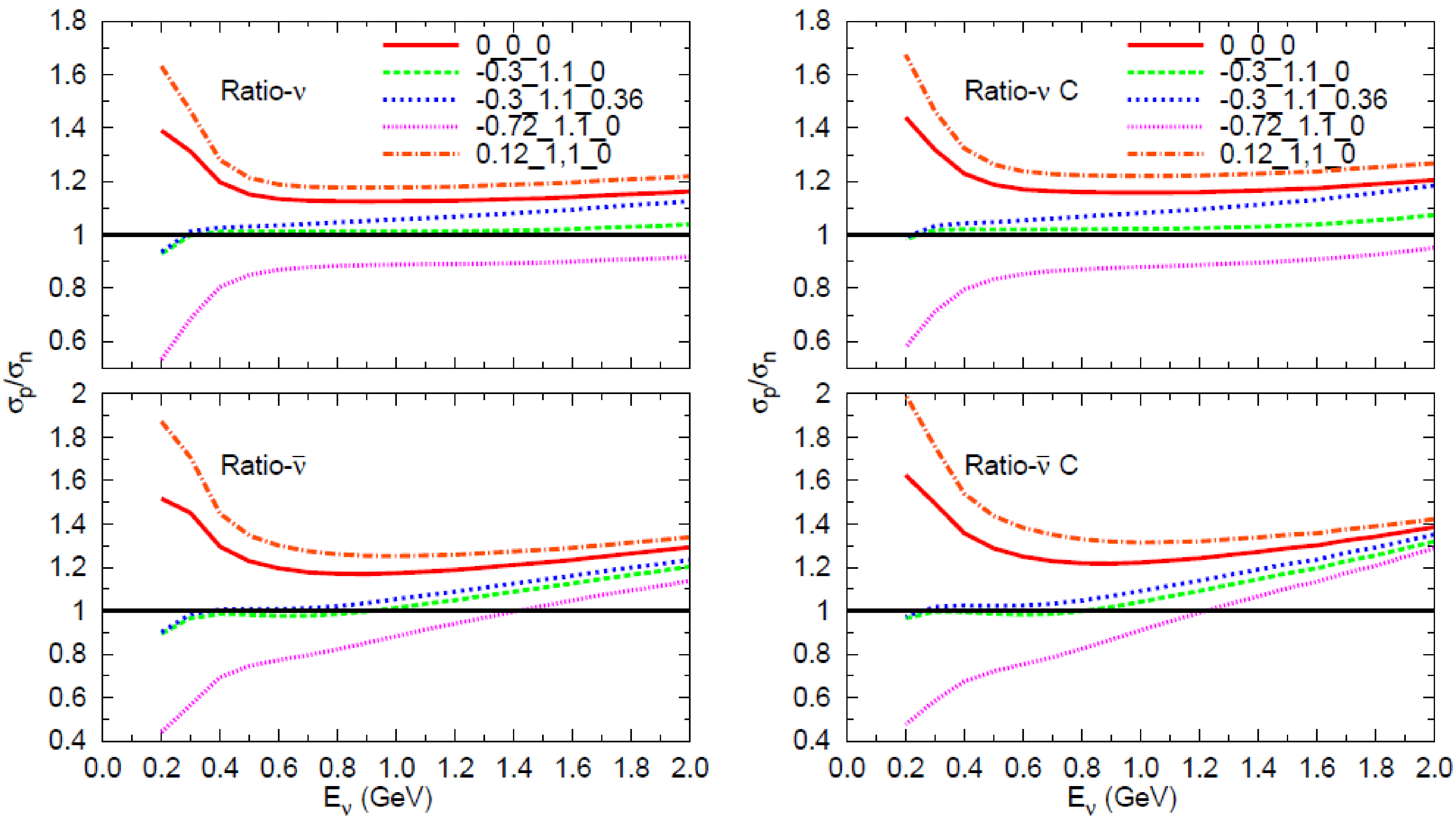
- Does this discrepancy come from the NEUT vs Wang et al. cross sections?
- Does this discrepancy matter?
  - For θ_{13}?: probably not.
  - For CP violation searches? perhaps...

NCγ and MiniBooNE+

- MiniBooNE+: Dharmapalan et al., arXiv:1310.0076
- Goal: Test the NC vs CC nature of the MiniBooNE low-energy excess
- Idea: Add scintillator material to detect neutrons
  - Low-energy CC interactions + n-capture in ∼10% of cases while
  - NC background NCπ and NCγ + n-capture in ∼50% of cases

- NCγp/NCγn ratio in our model (without nucleon FSI):

NCγ and MiniBooNE+



- NCγp/NCγn ratio = 1 for the Δ pole term
- NCγp/NCγn ratio ≠ 1 for the full model

NCγ and MiniBooNE+

- MiniBooNE+: Dharmapalan et al., arXiv:1310.0076
- Goal: Test the NC vs CC nature of the MiniBooNE low-energy excess
- Idea: Add scintillator material to detect neutrons
  - Low-energy CC interactions + n-capture in ~10% of cases while
  - NC background NCπ, NCγ + n-capture in ~50% of cases

- NCγp/NCγn ratio in our model (without nucleon FSI):
  - Depends on the strangeness content of the nucleon spin

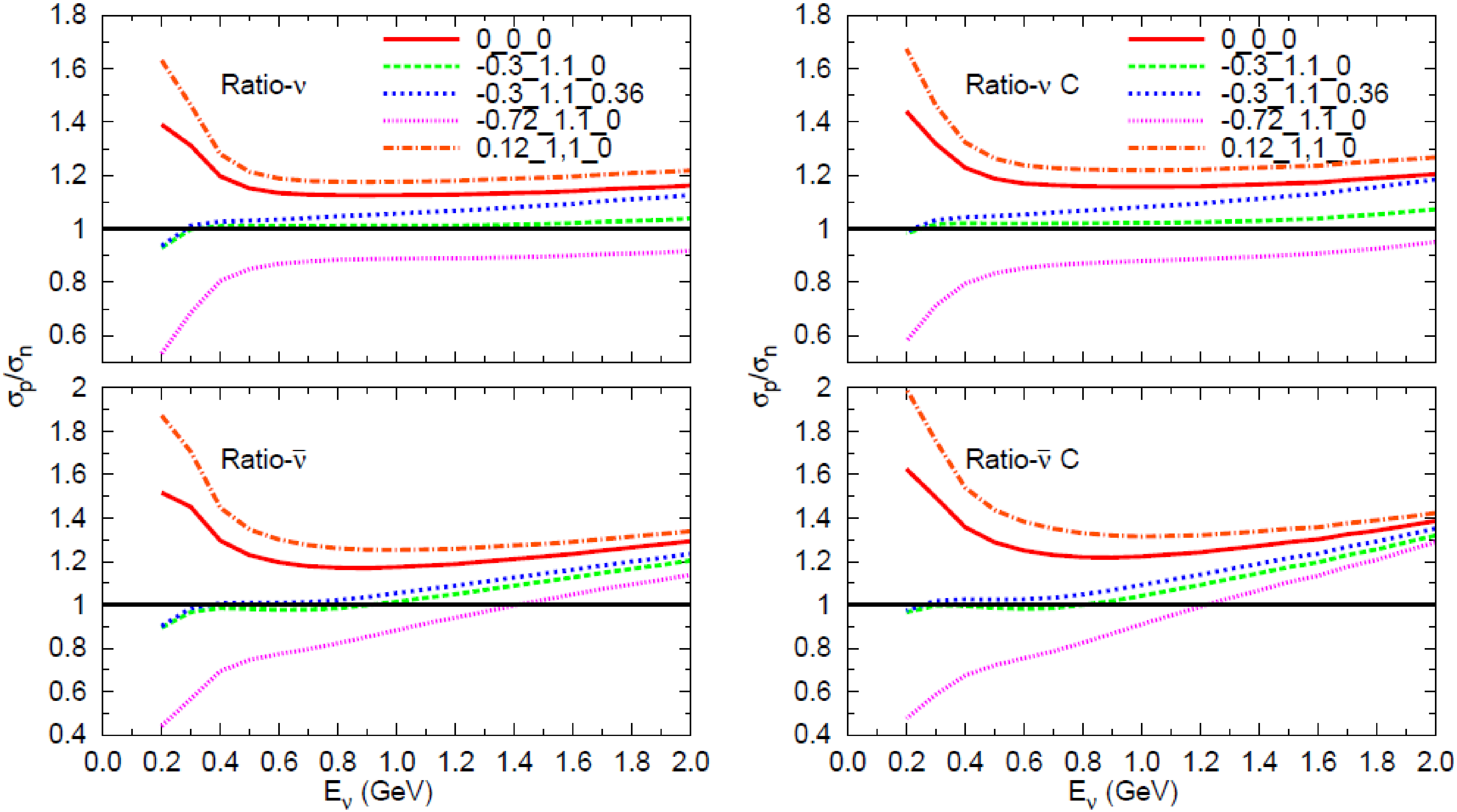
$$2\tilde{F}_A^{(p,n)} = \pm F_A + F_A^{(s)}$$

$$F_A^{(s)} = \frac{\Delta S + S_A Q^2}{(1 + Q^2/\Lambda_A^2)^2}$$

Parameter	Value
ΔS	-0.30 ± 0.42
Λ_A	1.1 ± 1.1
S_A	0.36 ± 0.50

Pate, Trujillo, arXiv:1308.5694

NCγ and MiniBooNE+



Conclusions

- We have studied photon emission induced by NC interactions with nucleons and nuclei in the energy region relevant for the MiniBooNE event excess
- Reaction dominated by Δ(1232) excitation
- Theoretical error dominated by N-Δ axial transition properties
- Large (~ 30 %) reduction on the cross section due to nuclear effects
- Results consistent with MiniBooNE's estimate for e-like events (in line with Zhang, Serot, PLB 719).
- Implications for T2K and MiniBooNE+ discussed