Neutrino Seminar Series

Fermilab

Photon Emission in NC interactions with nucleons and nuclei

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Introduction

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

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

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

    $\quad \hookrightarrow \gamma\, A$

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

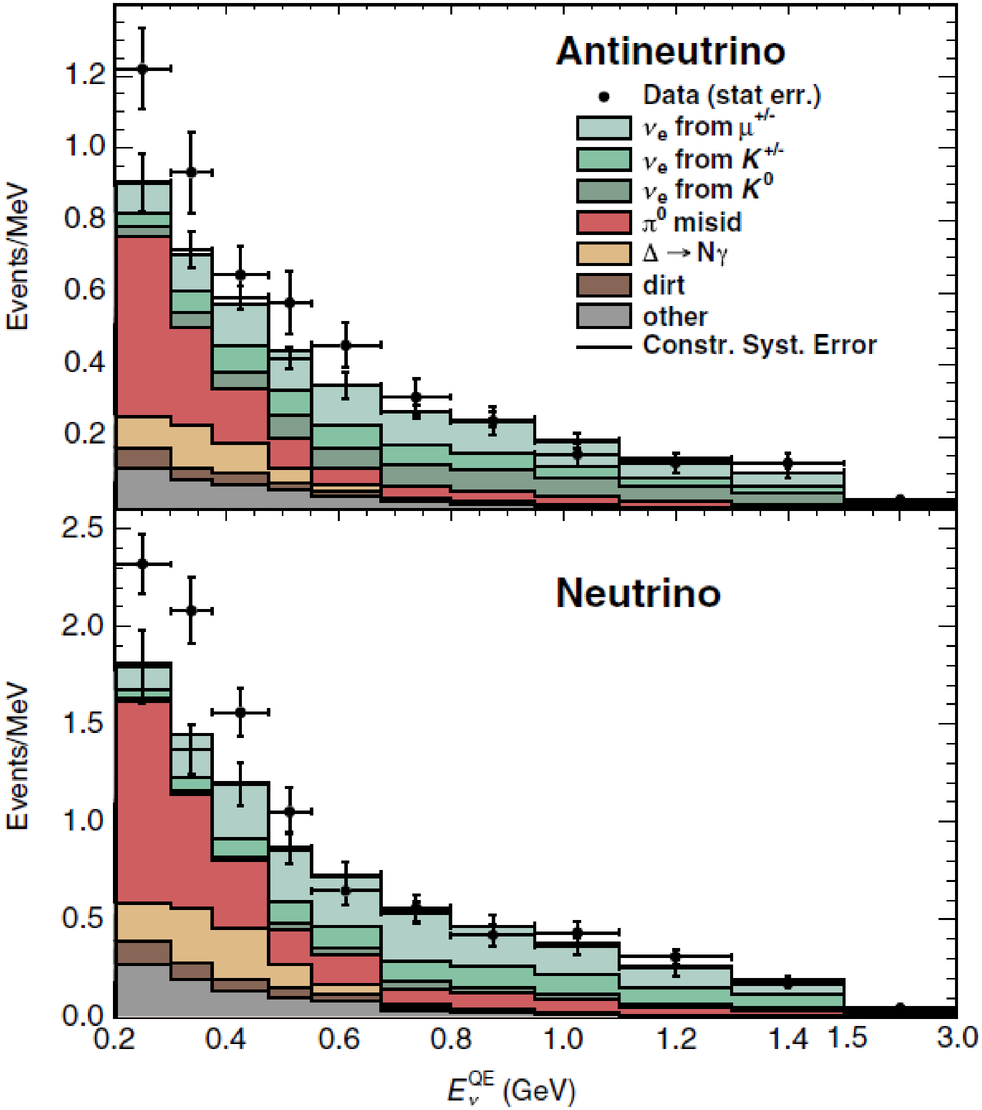
  - Small cross section (weak & e.m.)

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

Introduction

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



reconstructed ν energy

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

Introduction

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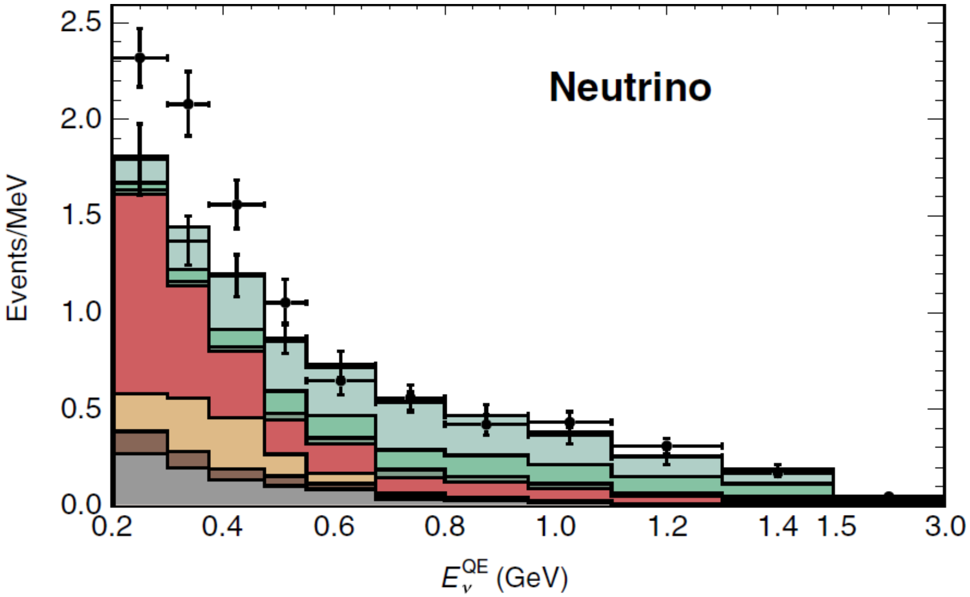

Aguilar-Arevalo et al., PRL110 (2013) 161801

- Unexplained excess of events at $200 < E_\nu^{QE} < 475$ MeV

Introduction

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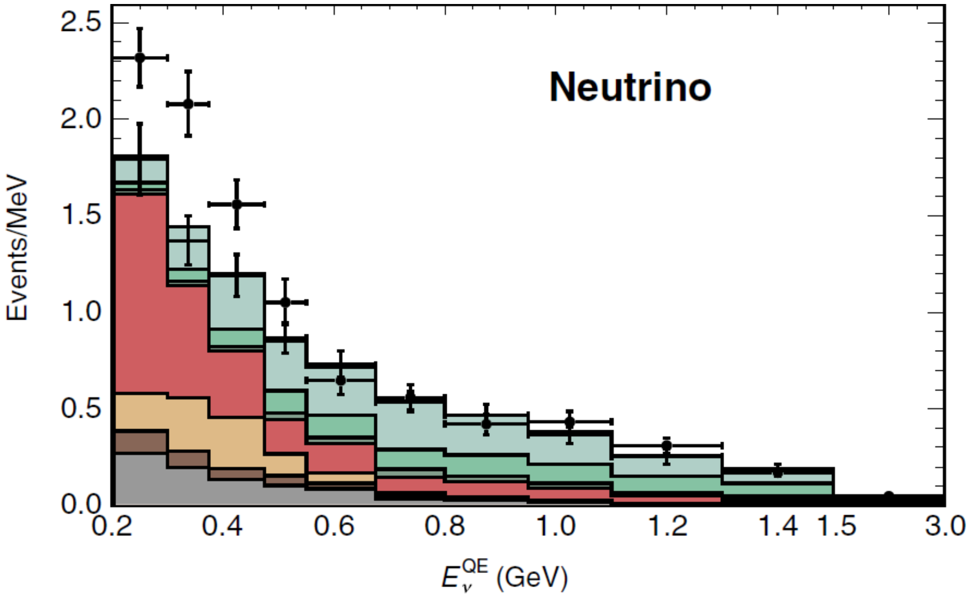
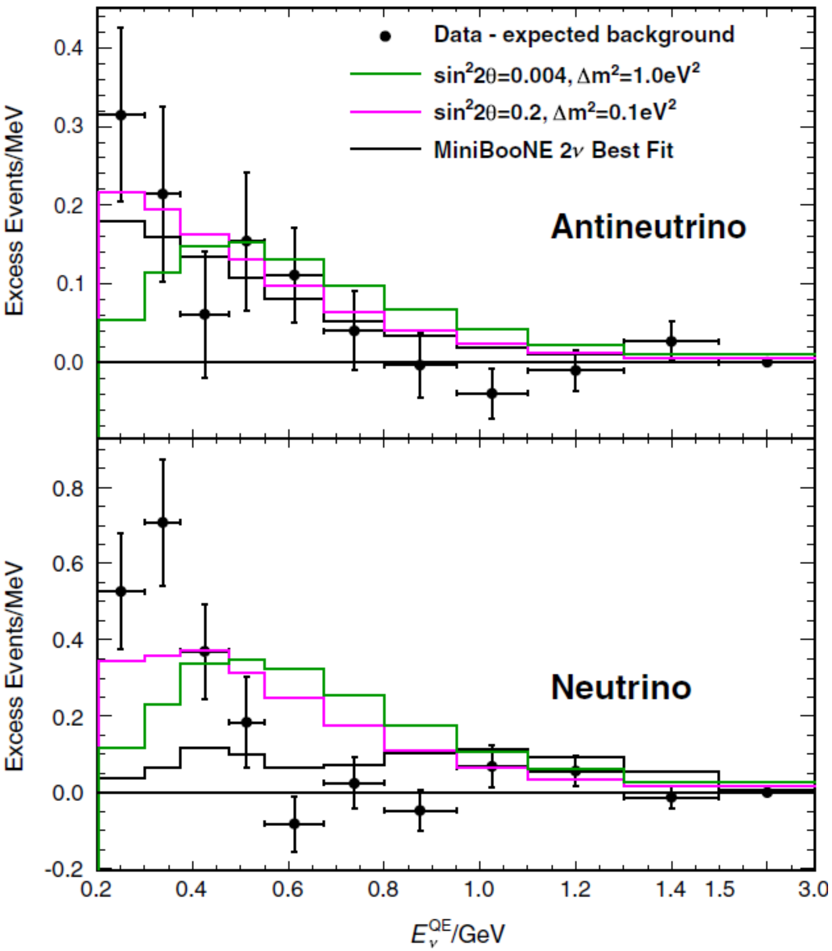


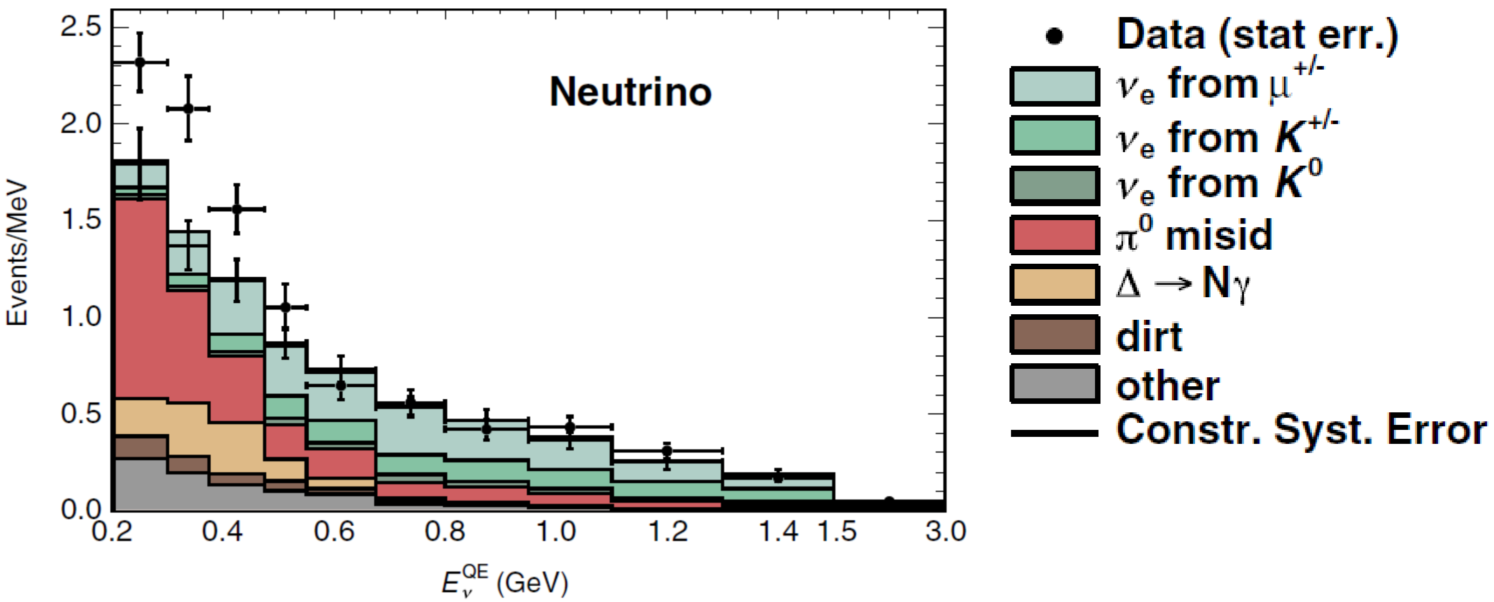
Aguilar-Arevalo et al., PRL110 (2013) 161801



- Only marginally compatible with a two-neutrino oscillation model
- Small overlap with LSND

Introduction

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

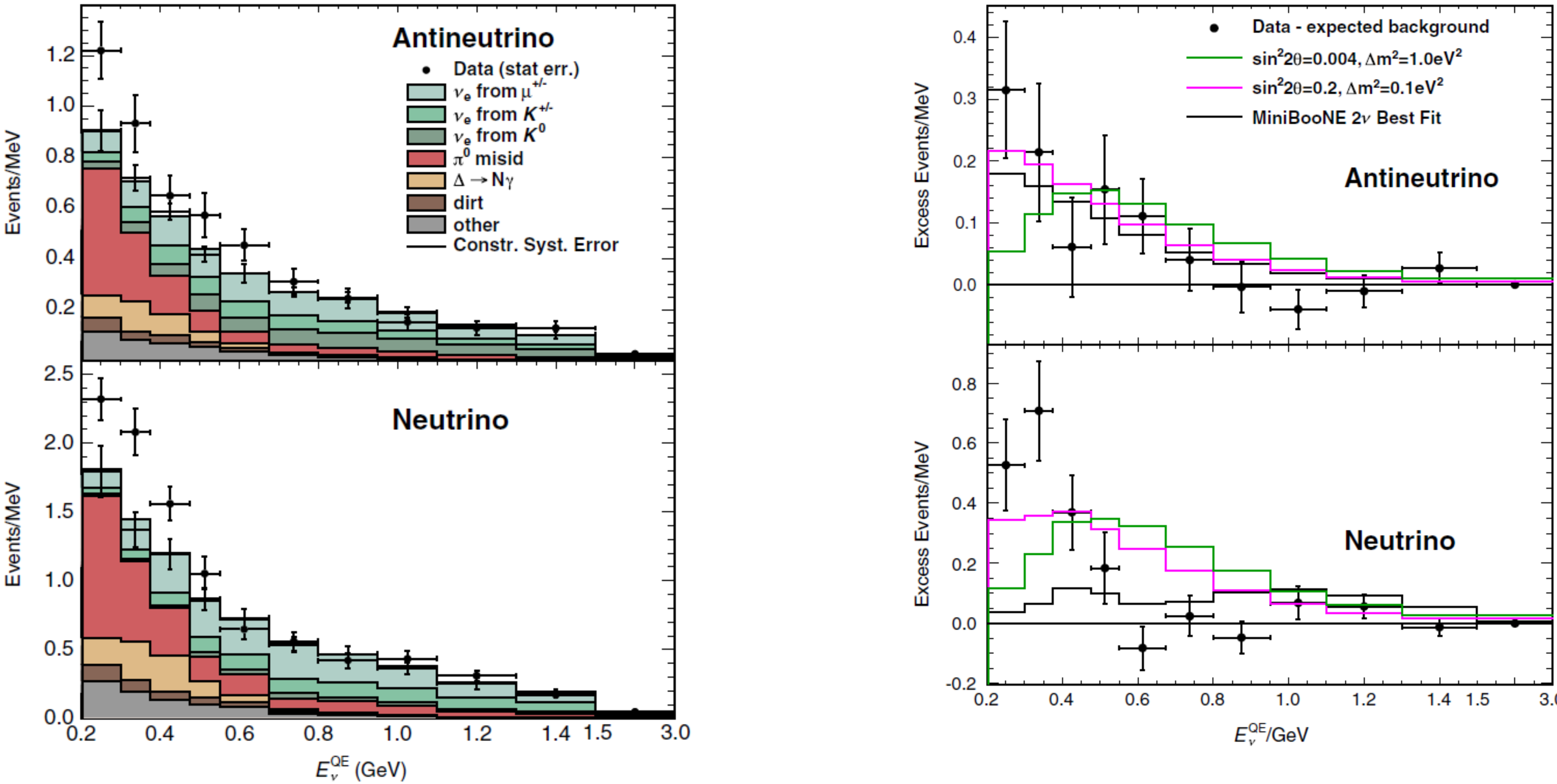


Aguilar-Arevalo et al., PRL110 (2013) 161801

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

Introduction

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

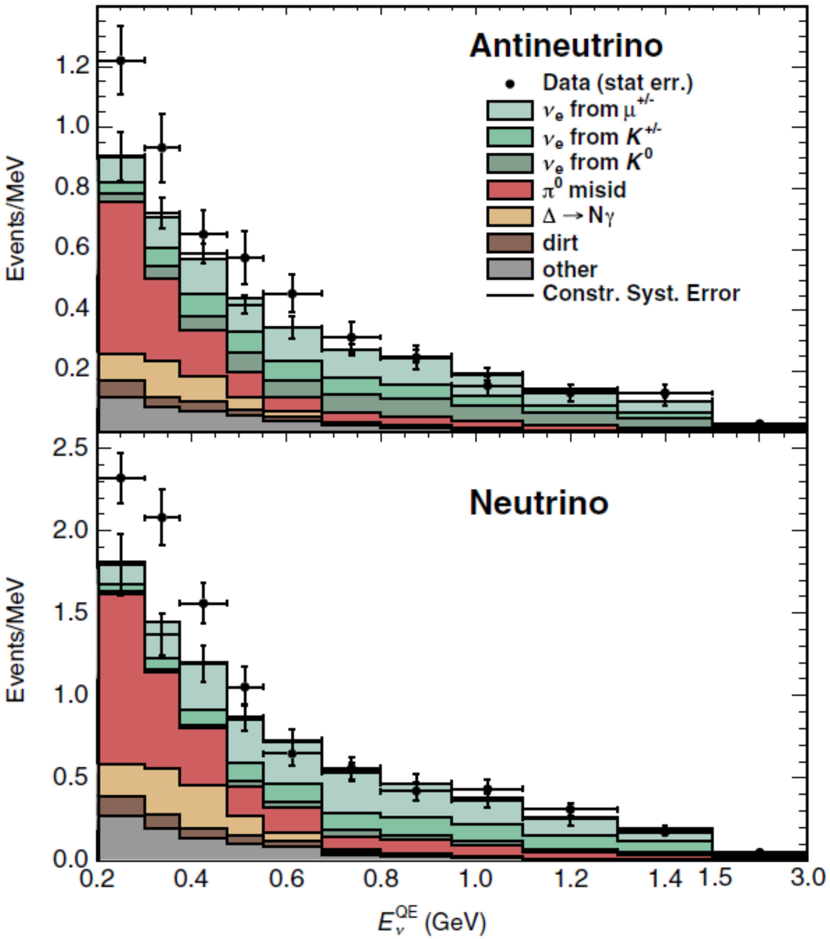


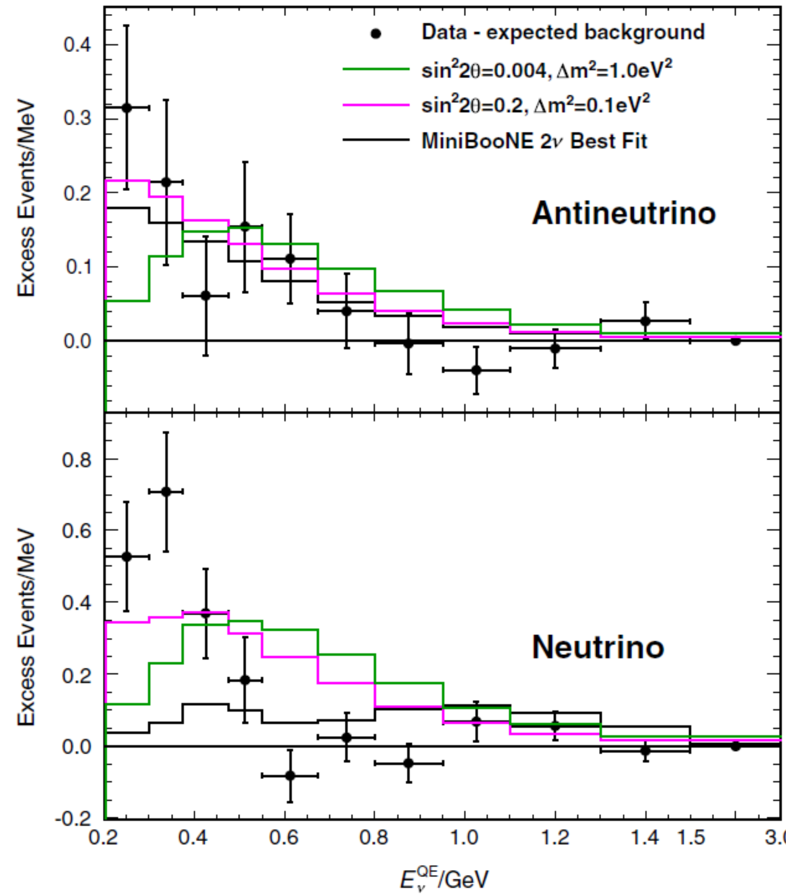
Aguilar-Arevalo et al., PRL110 (2013) 161801

- Oscillation hypothesis more probable
- Consistent in part with LSND and with the KARMEN limits

Introduction

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





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

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

Introduction

- e-like backgrounds @ MiniBooNE are constrained in situ…

Introduction

- e-like backgrounds @ MiniBooNE are constrained in situ…
  … but some are more constrained than others.
  - NC π^0
    - measured @ MiniBooNE
    - Rein-Sehgal resonance production model + non-resonant background
    - π FSI
  - NC $\Delta \to N \gamma$
    - relies on the determination of weak N-R vertices
    - No background
    - No coherent channel

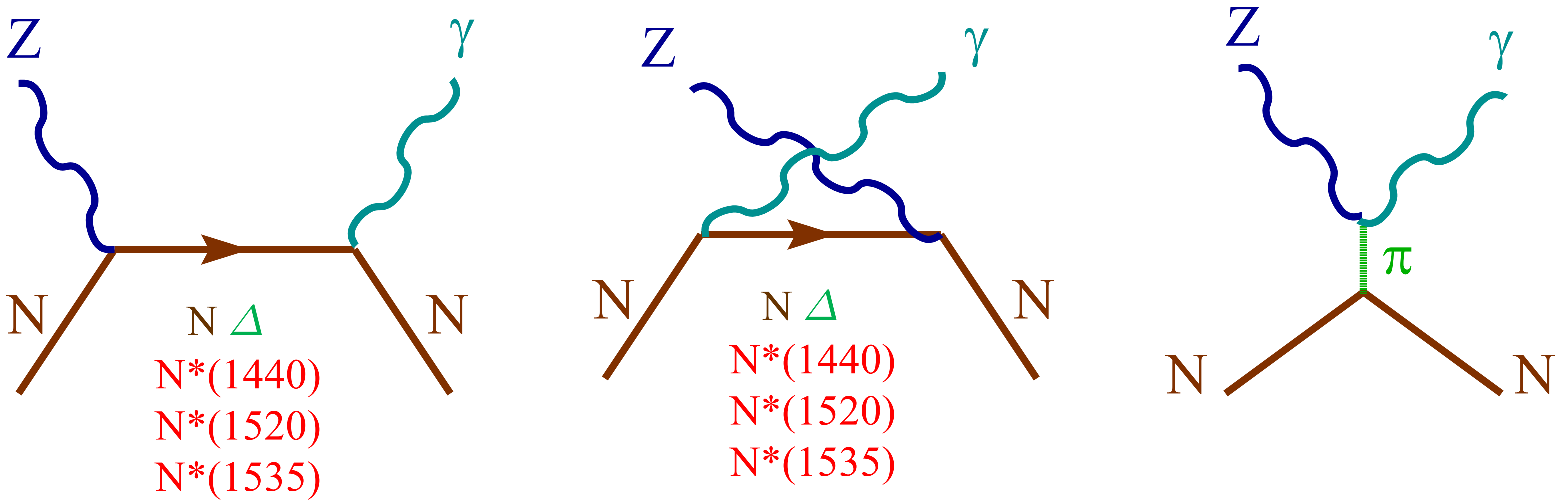
Introduction

- 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 ← Fermi constant

e ← electric charge

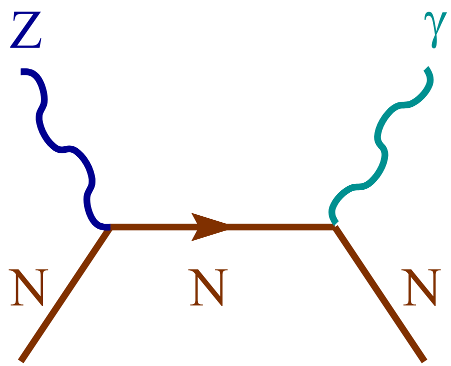
$\epsilon_\mu^{*(r)}$ ← photon polarization

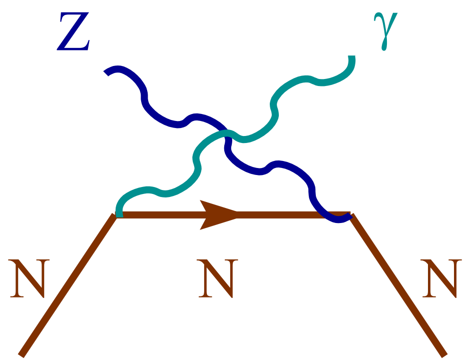
l_α ← NC for ν or $\bar{\nu}$

$\Gamma^{\mu\alpha}$ ← 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:

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

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

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

The model

- $\Delta(1232)$ pole terms:

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

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

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

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

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

The model

- $\Delta(1232)$ pole terms:

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

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

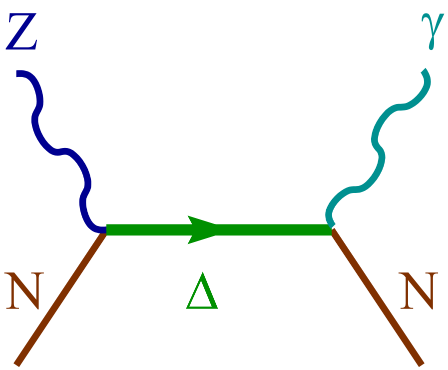
$$J^{\beta\mu}_{\mathrm{EM}}(p,q_\gamma) = \left[\frac{C^{(p,n)}_3(0)}{M}(g^{\beta\mu}\not{q}_\gamma - q^\beta_\gamma \gamma^\mu) + \frac{C^{(p,n)}_4(0)}{M^2}(g^{\beta\mu} q_\gamma\cdot p_\Delta - q^\beta_\gamma p^\mu_\Delta) + \frac{C^{(p,n)}_5(0)}{M^2}(g^{\beta\mu} q_\gamma\cdot p - q^\beta_\gamma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

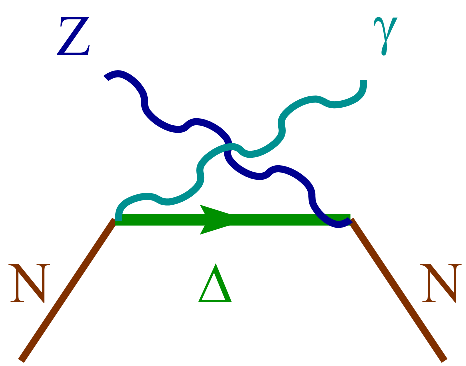
$$\tilde{C}^V_i = -(1 - 2\sin^2\theta_W) C^V_i \qquad C^{(p,n)}_i = -C^V_i$$

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

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

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

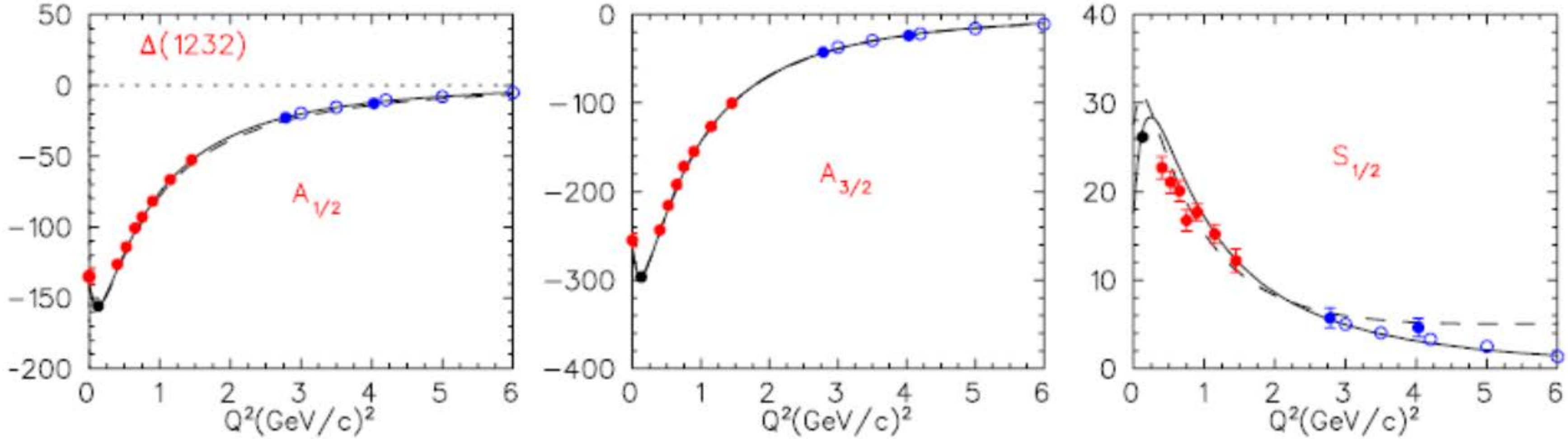
$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 3/2 \left| \epsilon_\mu^+ J_{\rm EM}^\mu \right| N, J_z = 1/2 \right\rangle \zeta$$

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

The model

- $\Delta(1232)$ pole terms:

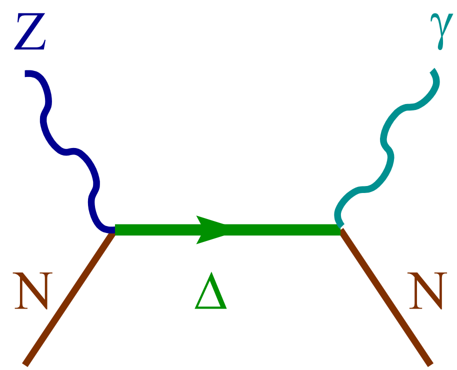
- N-Δ Vector form factors C_i^V can be obtained from helicity amplitudes extracted from π photo- and electro-production

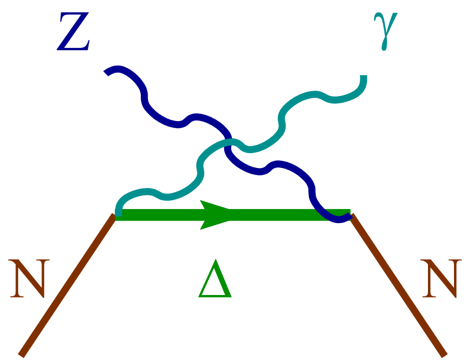


MAID, Tiator et al., EPJ Special Topics 198 (2011)

The model

- $\Delta(1232)$ pole terms:





- N-Δ Axial form factors C_i^A

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

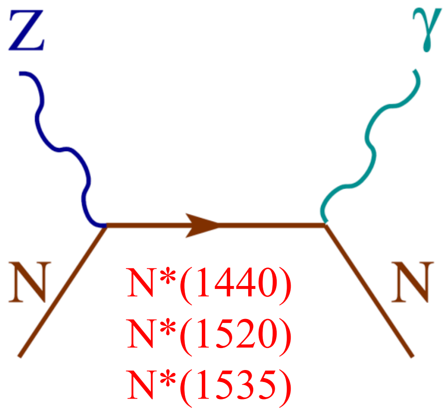
$$C_5^A = C_5^A(0) \left(1 + \frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$$

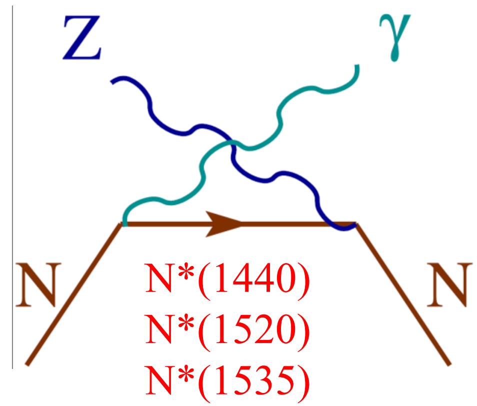
  - $C^A_5(0) = 1.00 \pm 0.11$, $M_{A\,\Delta} = 0.93 \pm 0.07$ GeV

    Hernandez et al., PRD 81 (2010)

The model

- N* pole terms:





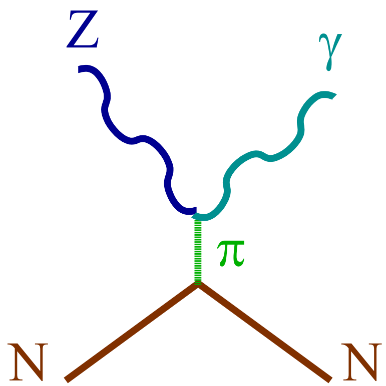
- N-N* Vector form factors can be obtained from helicity amplitudes
- N-N* Axial form factors:
  - PCAC $q^\alpha A_\alpha \approx 0$
  - π-pole dominance of the pseudoscalar form factor: $F_P,\ C_6^A$
  - Dipole q^2 dependence

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

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

The model

- π pole term:



- from the anomalous part of the Lagrangian

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

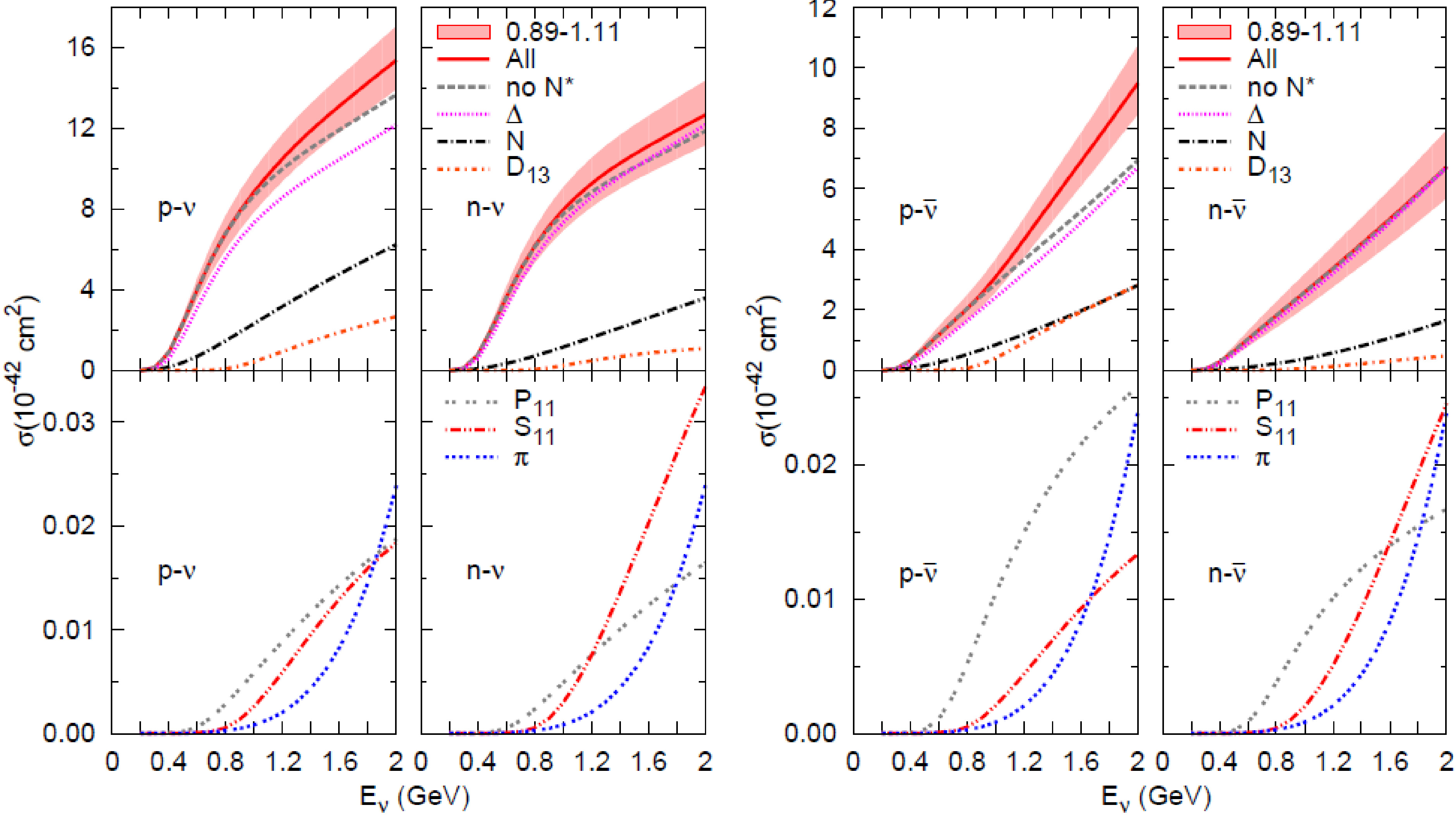
$$D_\pi(p) = \frac{1}{p^2 - m_\pi^2}$$ ← π propagator

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

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

Results on nucleons

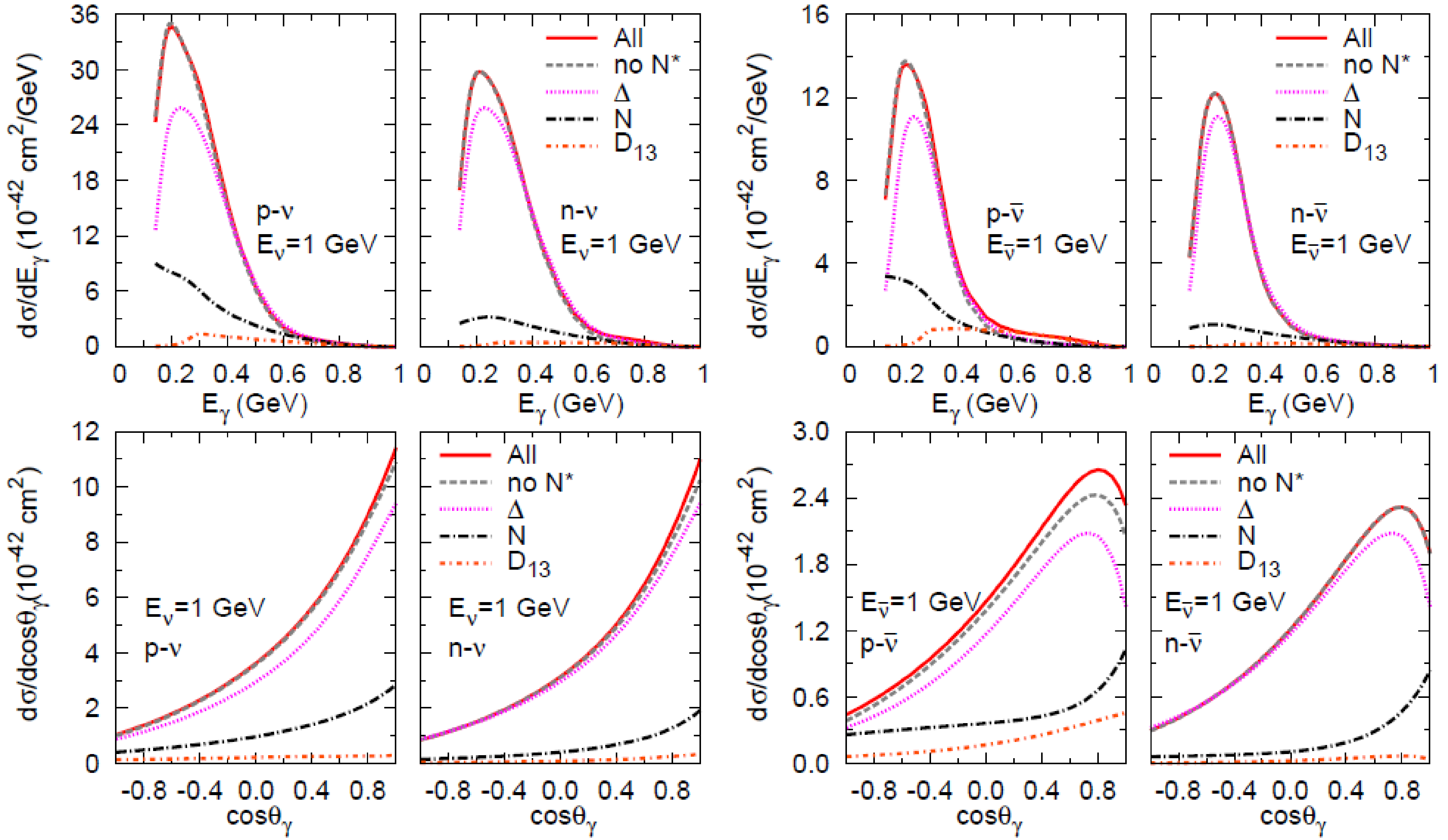
- Integrated cross sections (E_γ> 140 MeV)



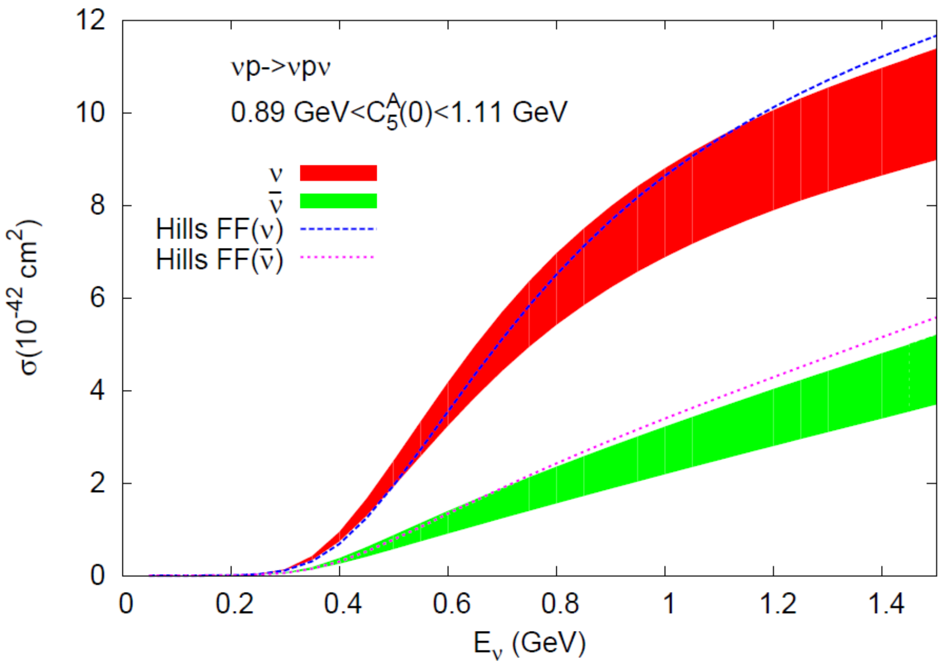
- Error band: $C^A_5(0)$ =1.00 ± 0.11 Hernandez et al., PRD 81 (2010)

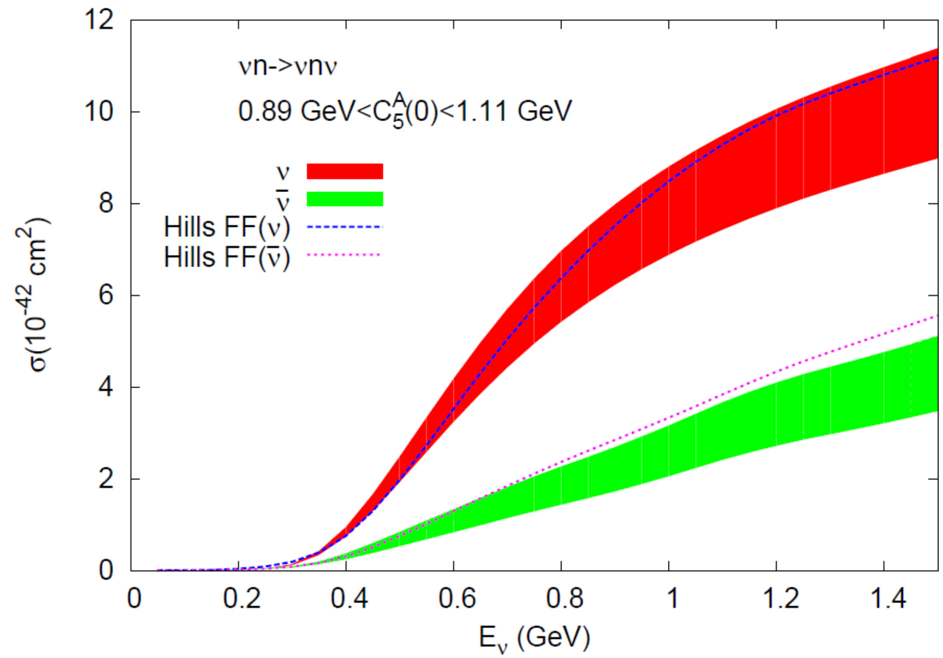
Results on nucleons

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



Comparison





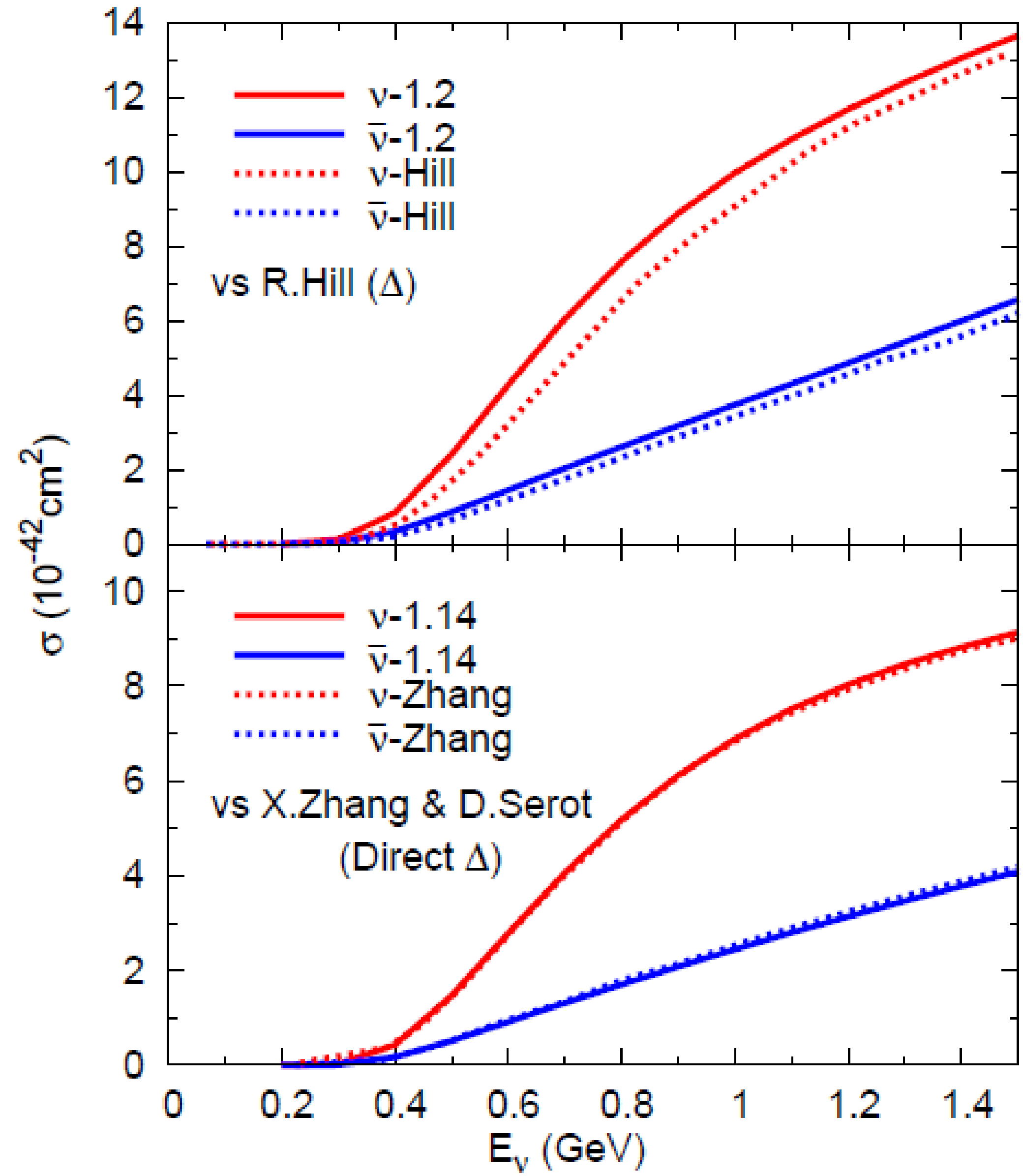
- N+Δ only
- Error band: $C^A_5(0)$ =1.00 ± 0.11 Hernandez et al., PRD 81 (2010)
- Main differences with R. Hill, PRD 81 (2010)
  - $C^A_5(0)$ = 1.00 ± 0.11 GeV vs 1.2
  - Energy dependent Γ_Δ vs Γ_Δ = const = 120 MeV
  - For nucleon pole diags.: M_A = 1 vs 1.2 GeV

Comparison

- Only Δ

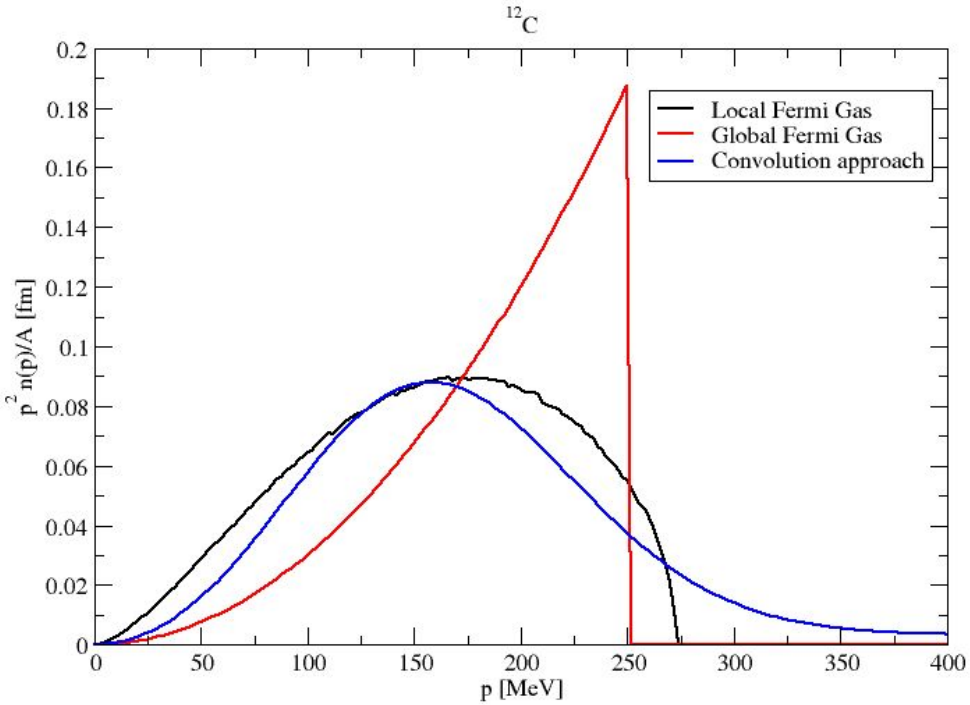
- $C^A_5(0) = 1.2$
- No cut in E_γ

- $C^A_5(0) = 1.14$
- $E_\gamma > 200$ 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 $P_{\mathrm{Pauli}} = 1 - \Theta(p_F(r) - |\vec{p}|)$
- 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

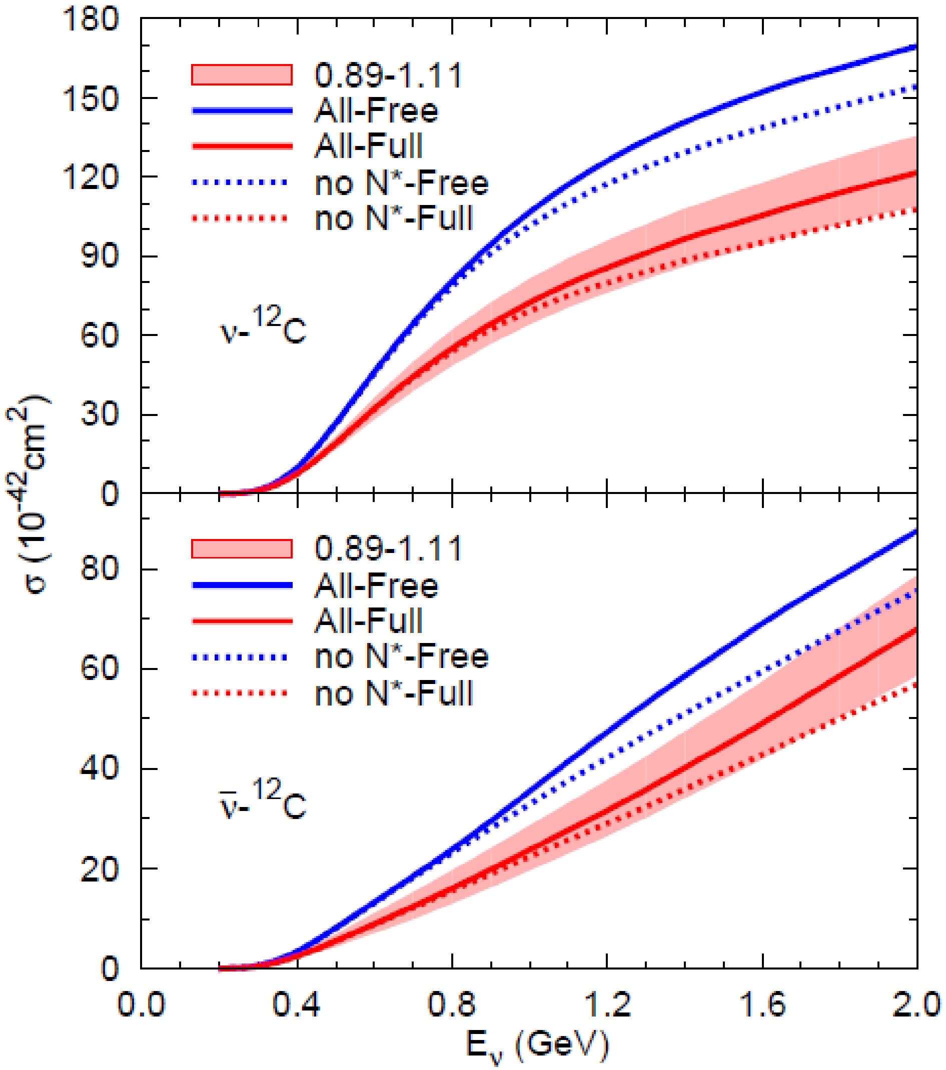
$\mathrm{Re}\Sigma_\Delta(\rho) \approx 0$

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

- $\Delta\, N \to N\, N$
- $\Delta\, N \to N\, N\, \pi$
- $\Delta\, N\, N \to N\, N\, N$

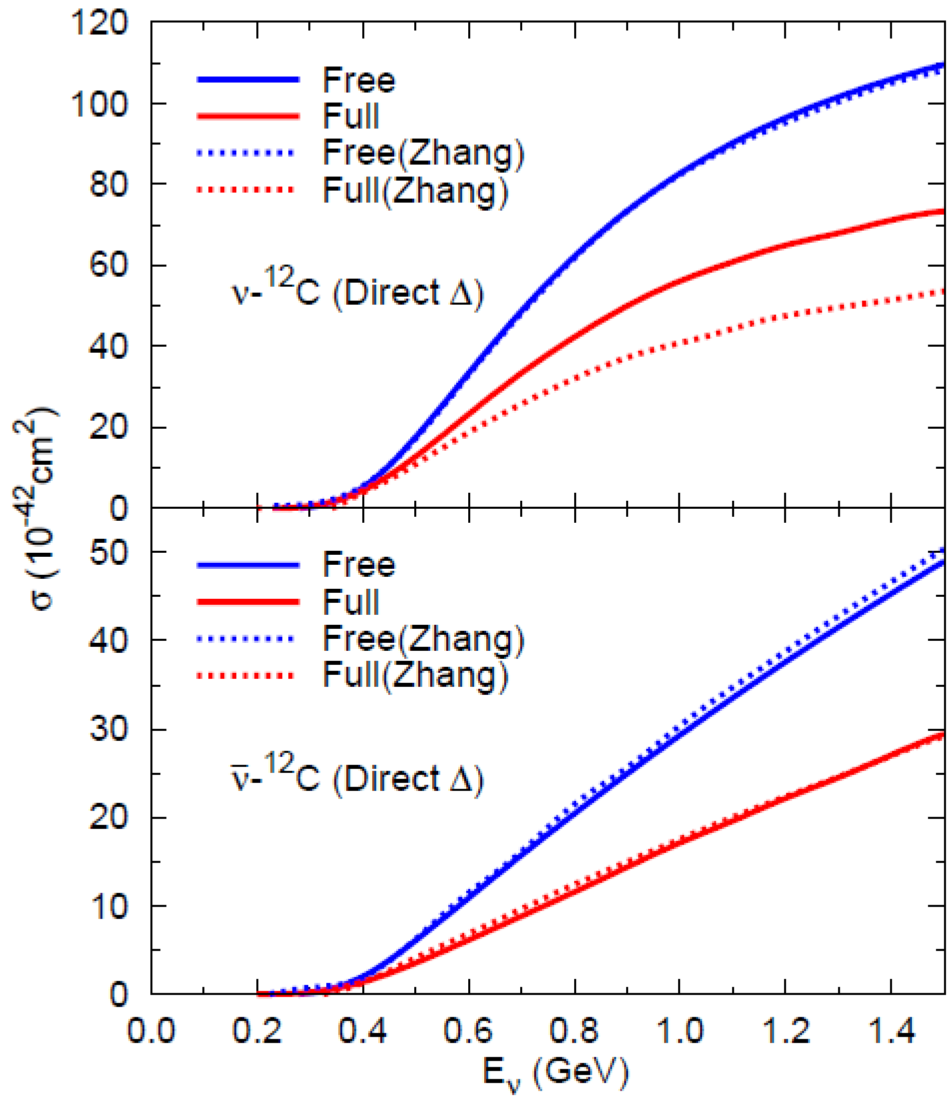
Results

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



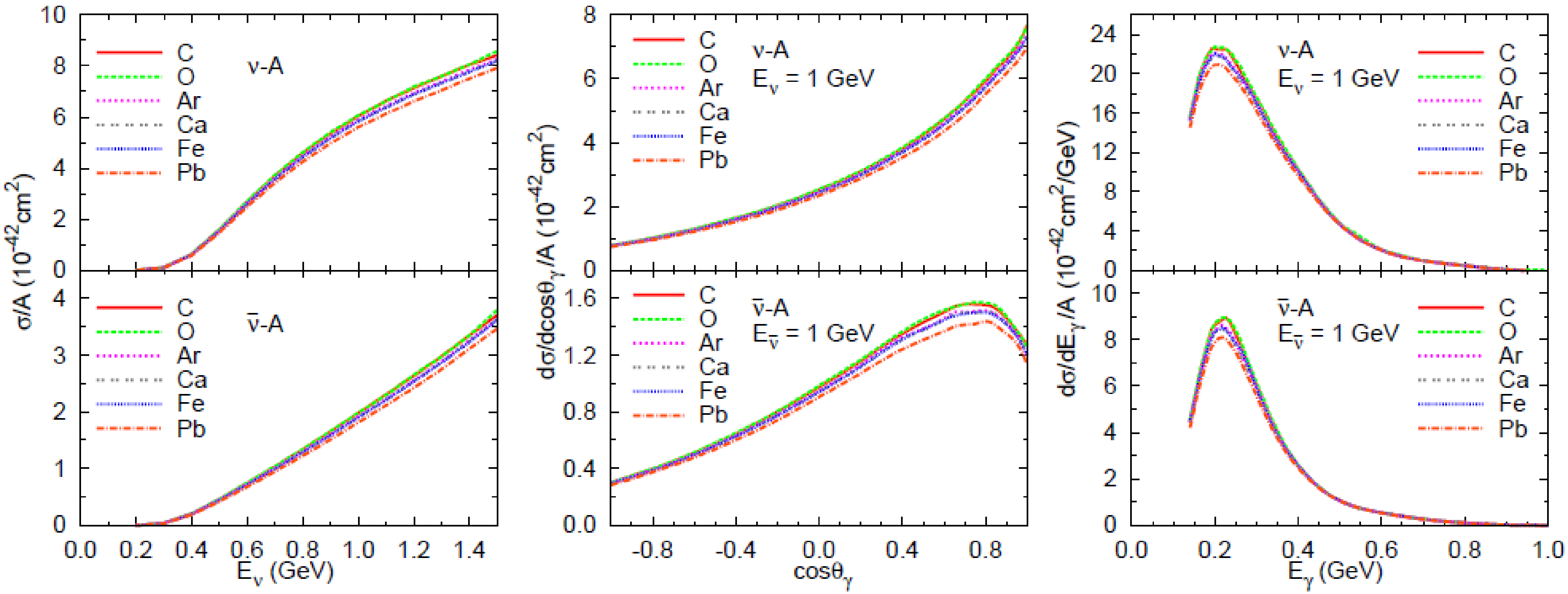
Comparison

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

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

  - 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
    - similar to the sum over all momenta for Cohπ^0 photoproduction
      Carrasco et al., NPA565 (1993)

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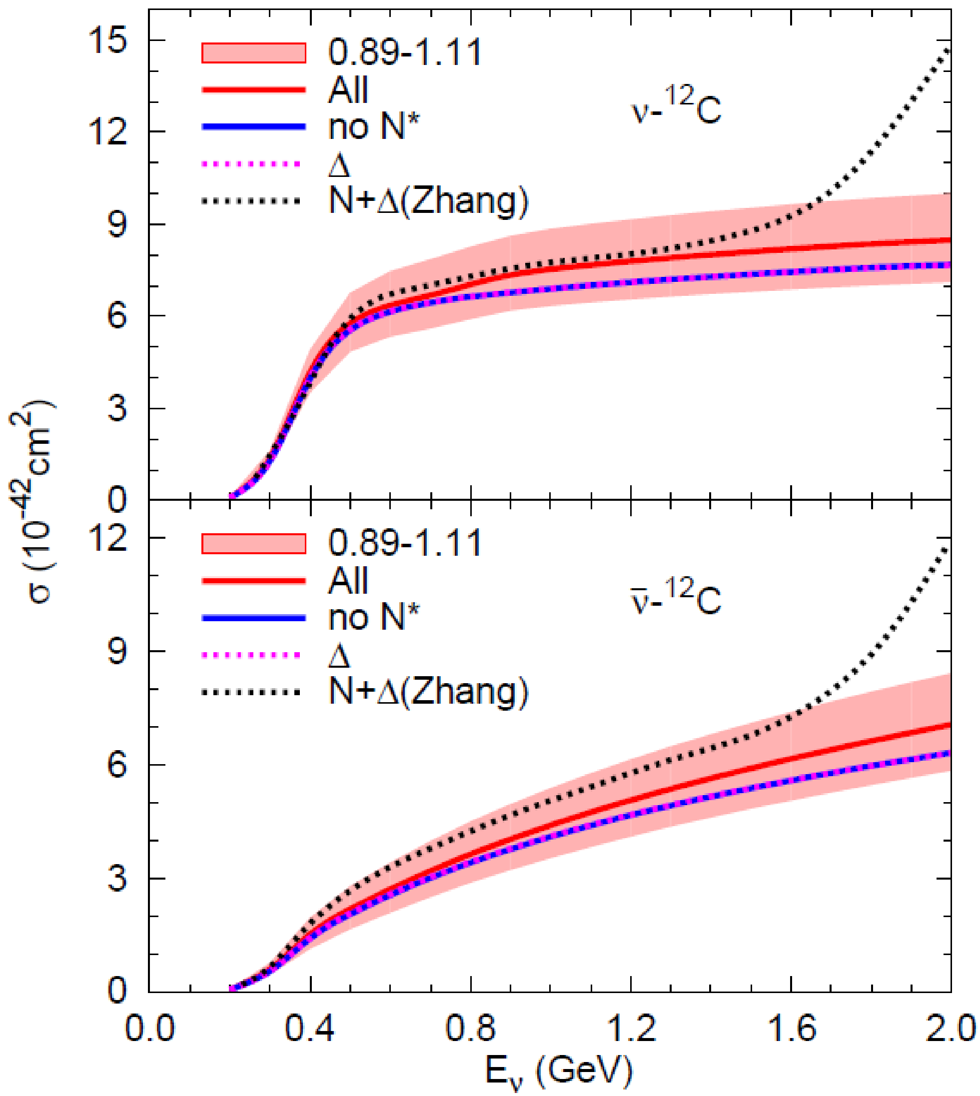
    - equally shared by initial and final nucleons
    - Δ momentum well defined (local treatment)

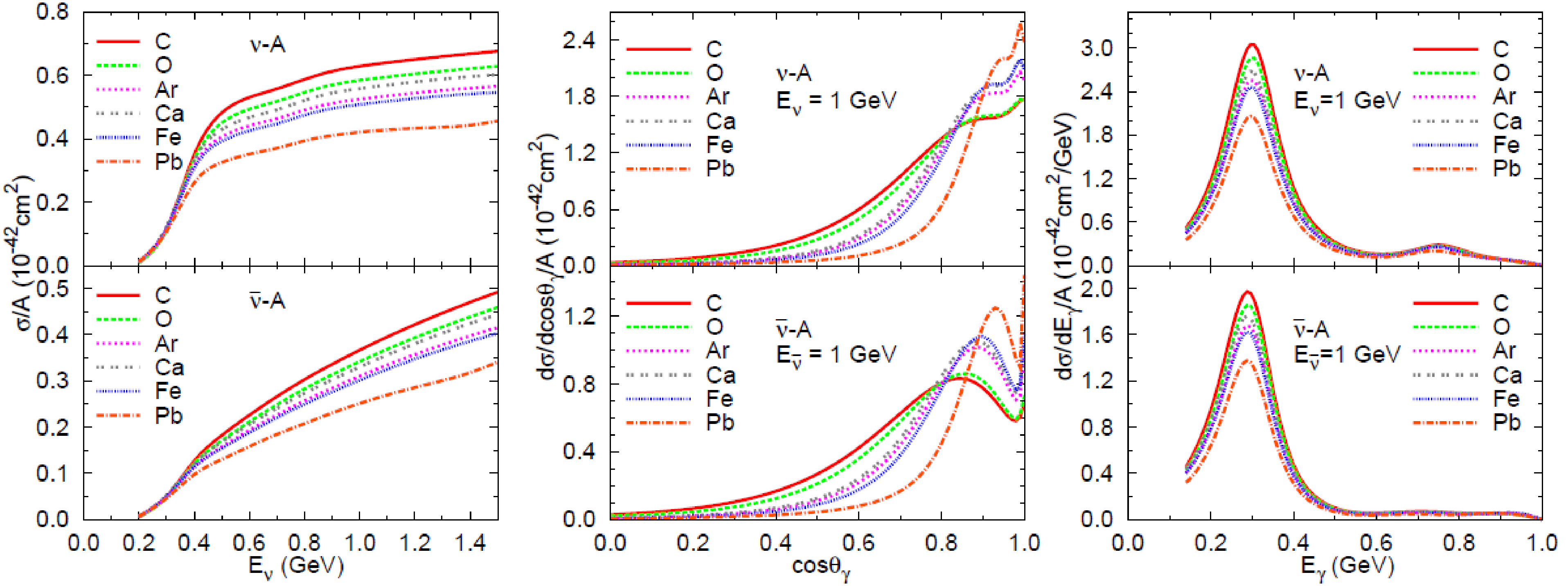
Results and Comparison

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



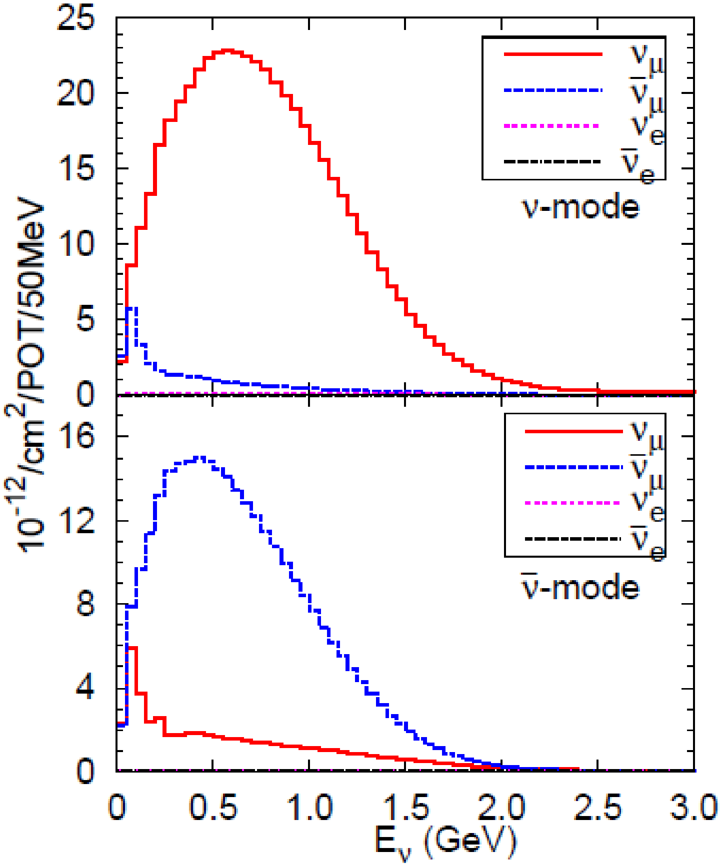
Results

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



NCγ events at MiniBooNE

- **Target**: CH_2 Aguilar-Arevalo et al, PRL 110 (2013)
- **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)



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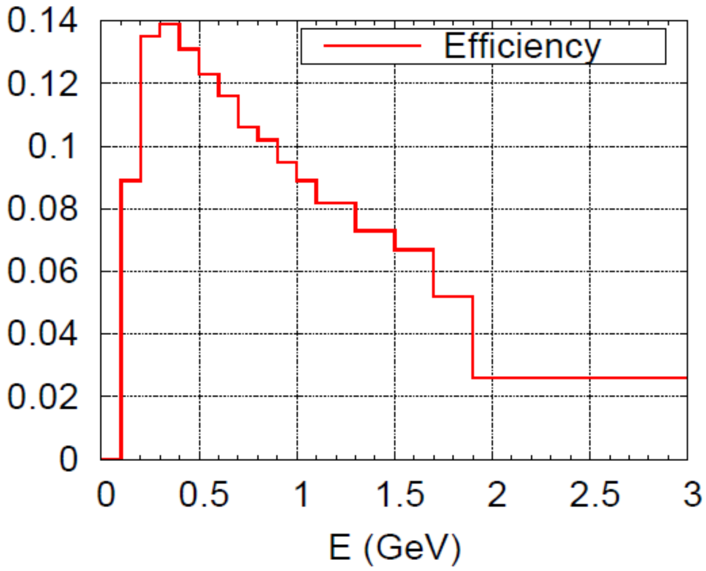


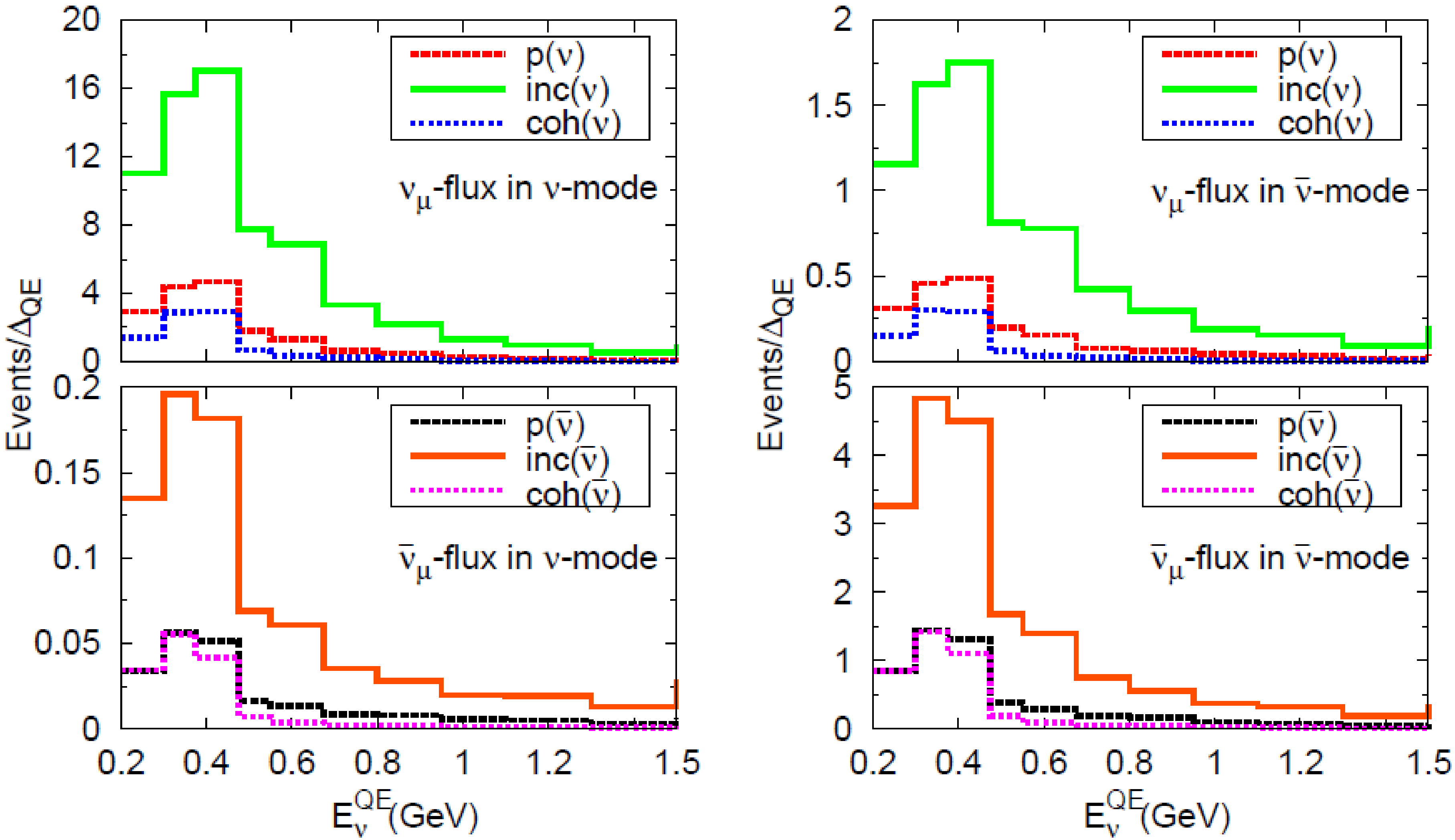
NCγ events

- In the Lab. Frame:

$$\frac{dN}{dE_\gamma d\cos\theta_\gamma} = e(E_\gamma) \sum_{l=\nu_\mu,\bar{\nu}_\mu,\ldots} N_{\mathrm{POT}}^{(l)} \sum_{t=p,\,A} N_t \int dE_\nu \phi_l(E_\nu) \frac{d\sigma_{l\,t}(E_\nu)}{dE_\gamma d\cos\theta_\gamma}$$

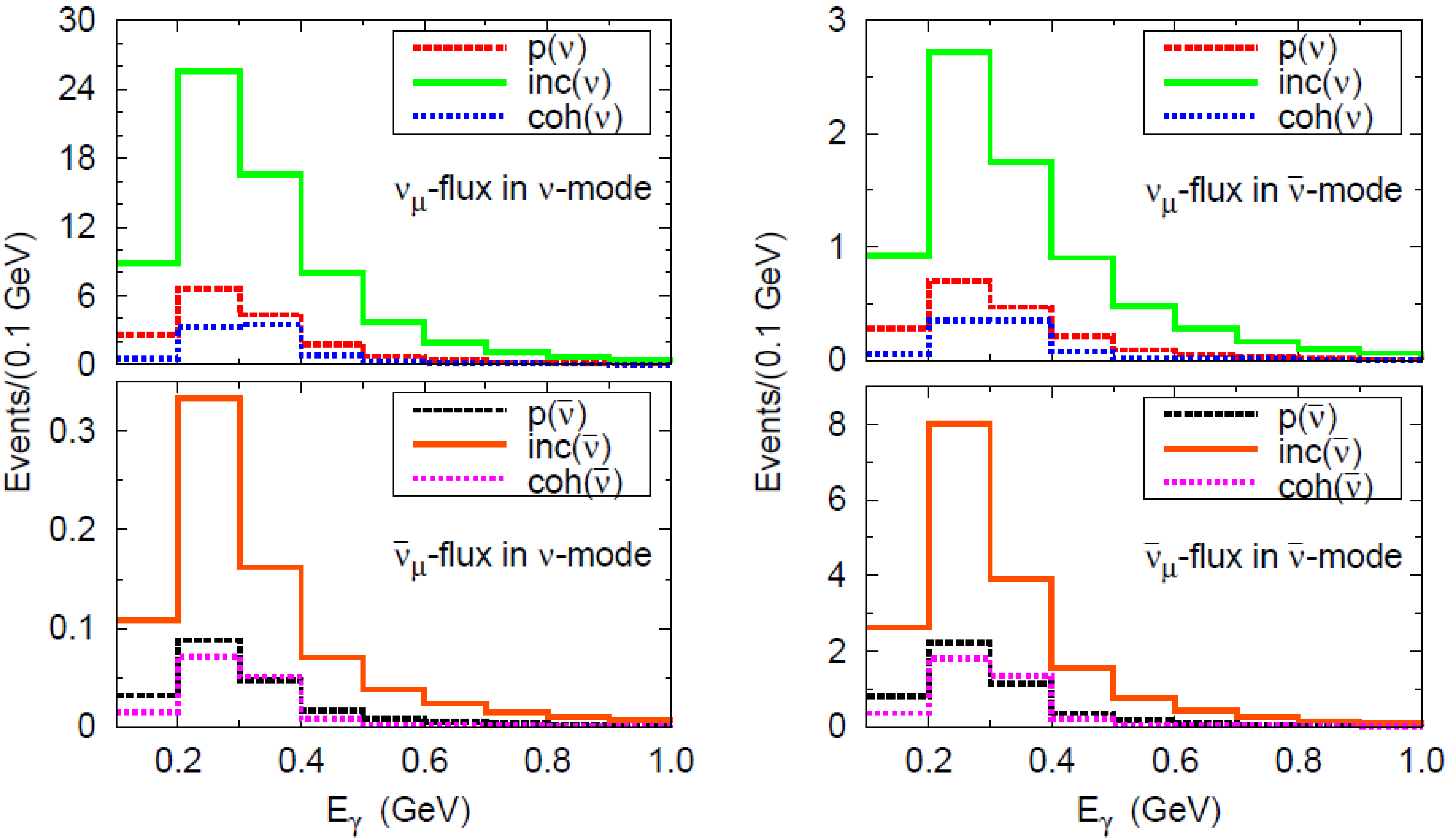
$$\frac{dN}{dE_\nu^{\mathrm{QE}}} = \int dE_\gamma d\cos\theta_\gamma \frac{dN}{dE_\gamma d\cos\theta_\gamma} \delta\left(E_\nu^{\mathrm{QE}} - \frac{2(m_N - E_B)E_\gamma - E_B^2 + 2m_N E_B}{2\left[(m_N - E_B) - E_\gamma(1-\cos\theta_\gamma)\right]}\right) .$$

NCγ events at MiniBooNE



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

NCγ events at MiniBooNE



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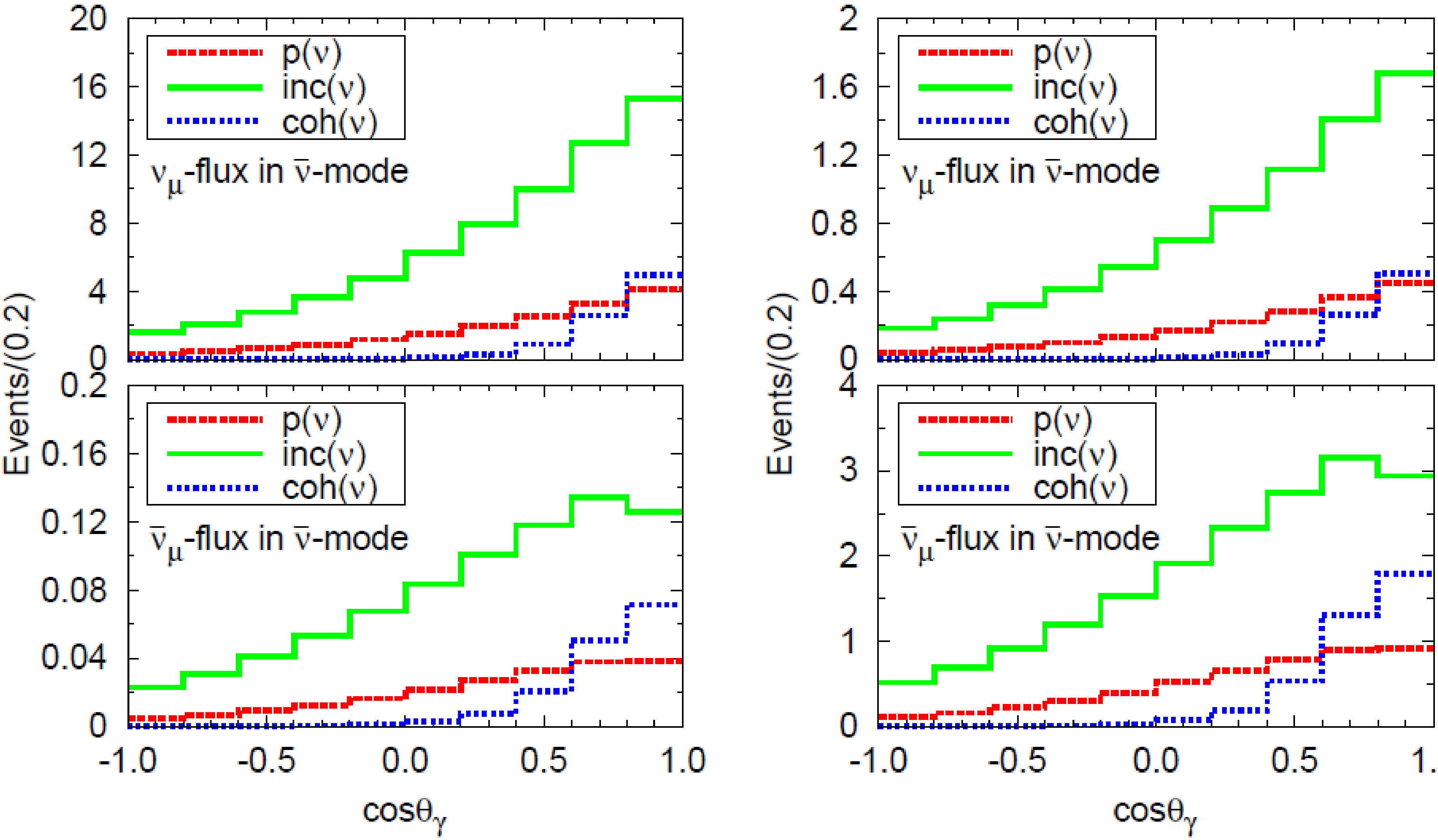

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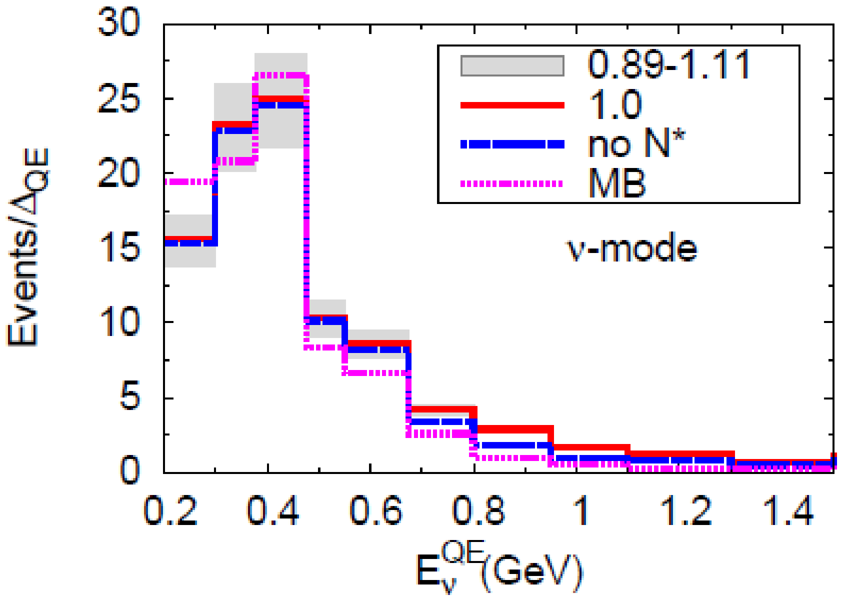
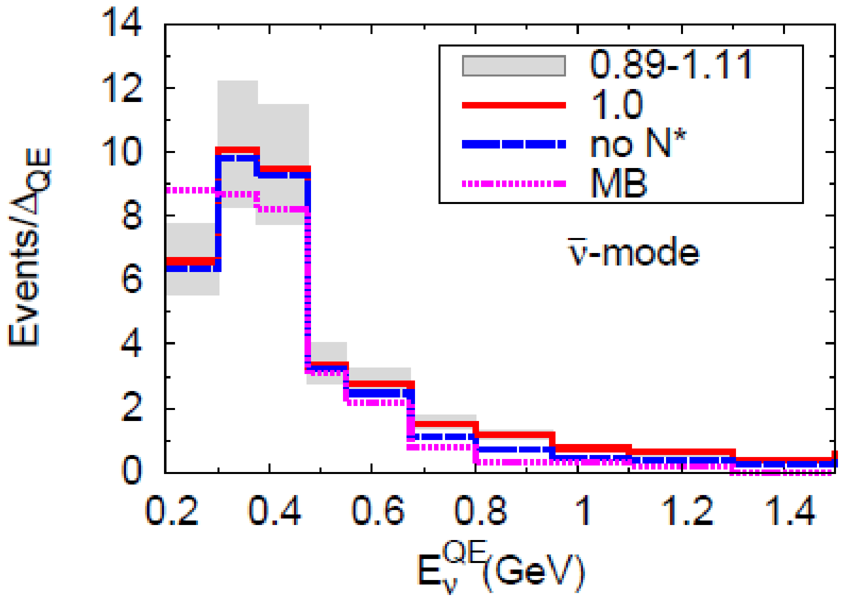
- **Comparison** to the MiniBooNE estimate





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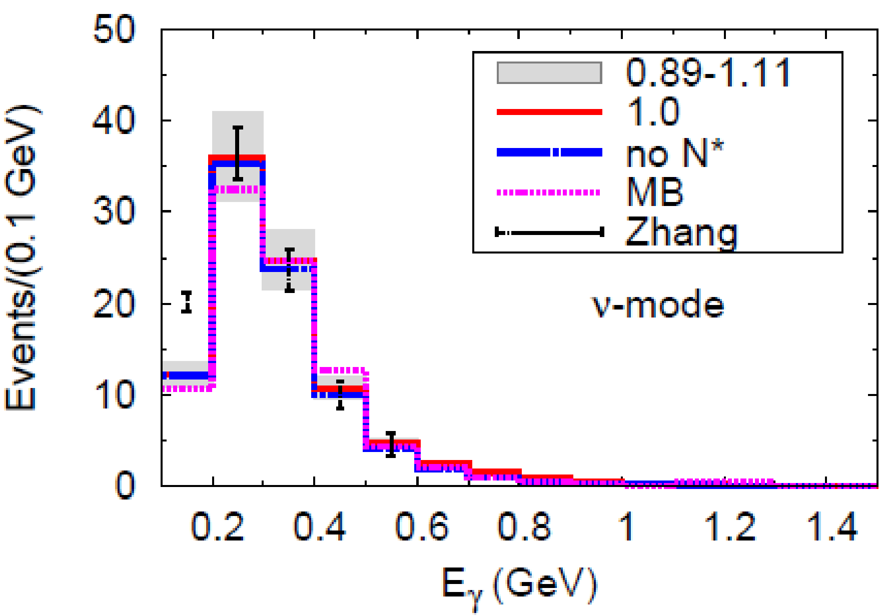
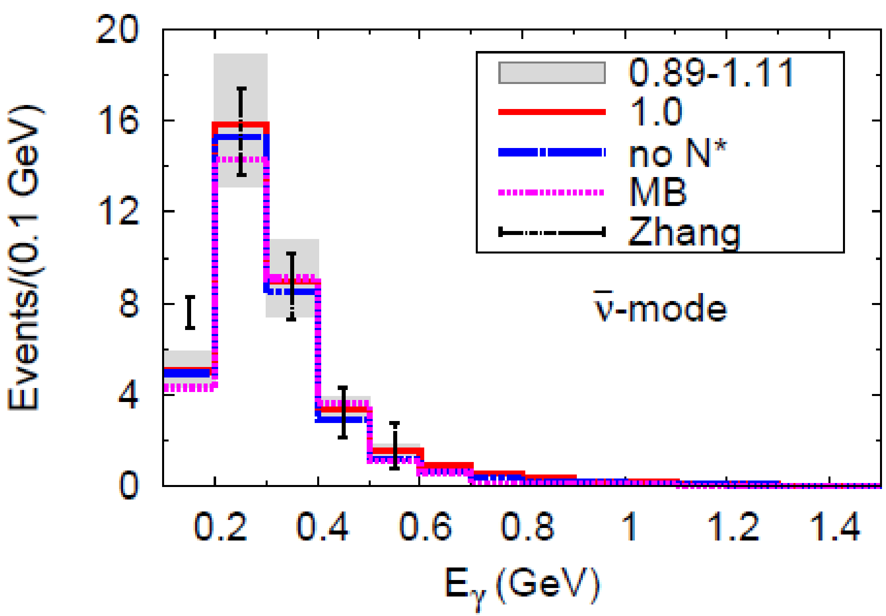
- Comparison to the MiniBooNE estimate and to Zhang, Serot, PLB 719 (2013)





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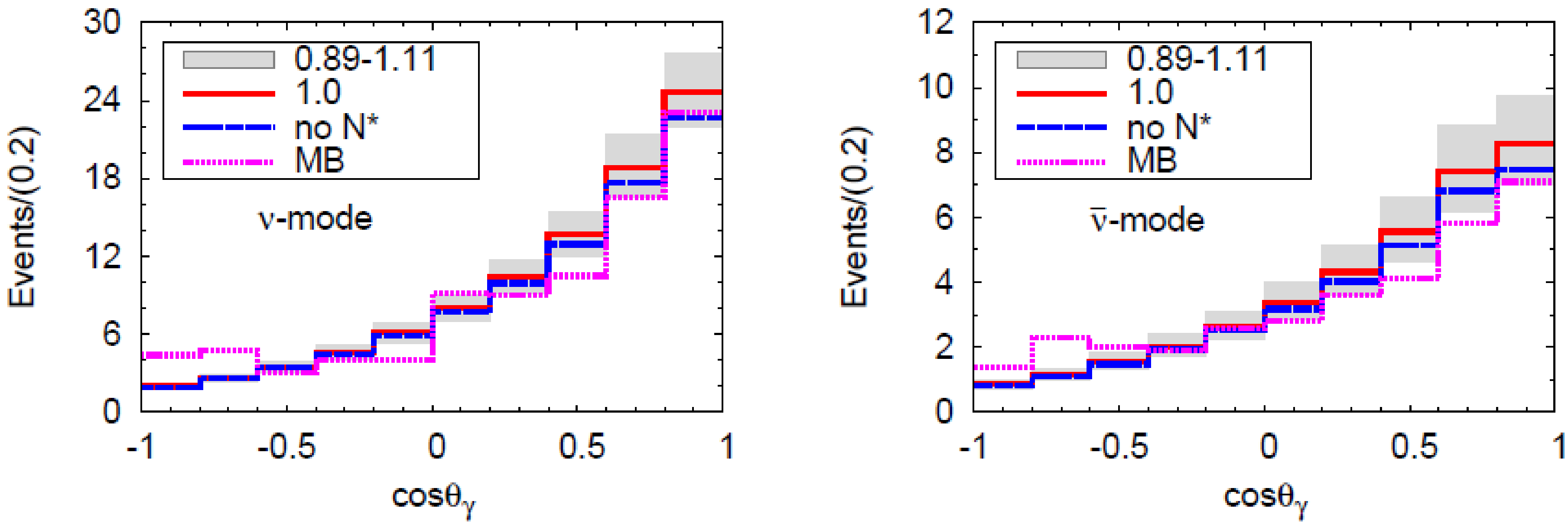
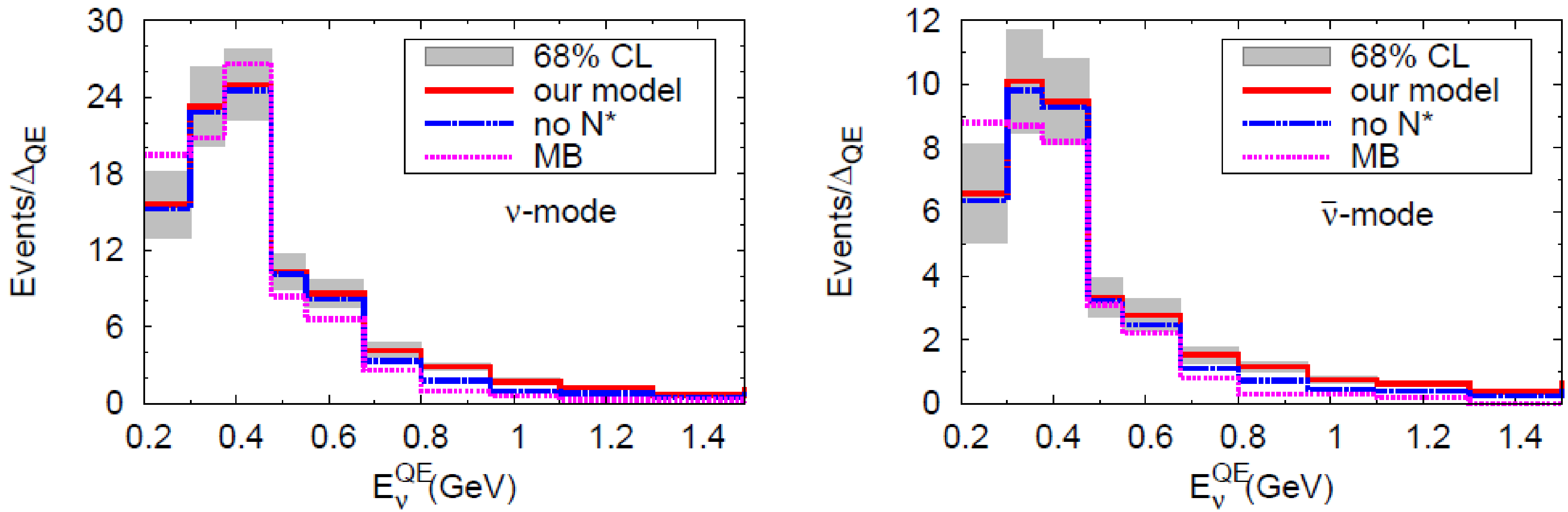


NCγ events at MiniBooNE

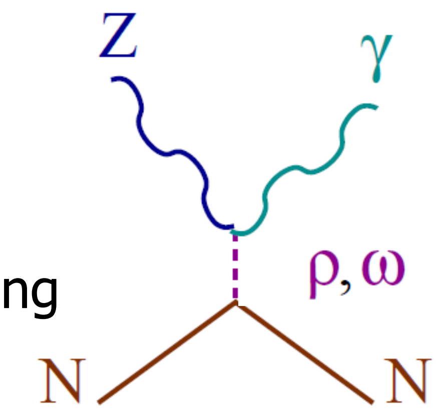
- Extended error budget

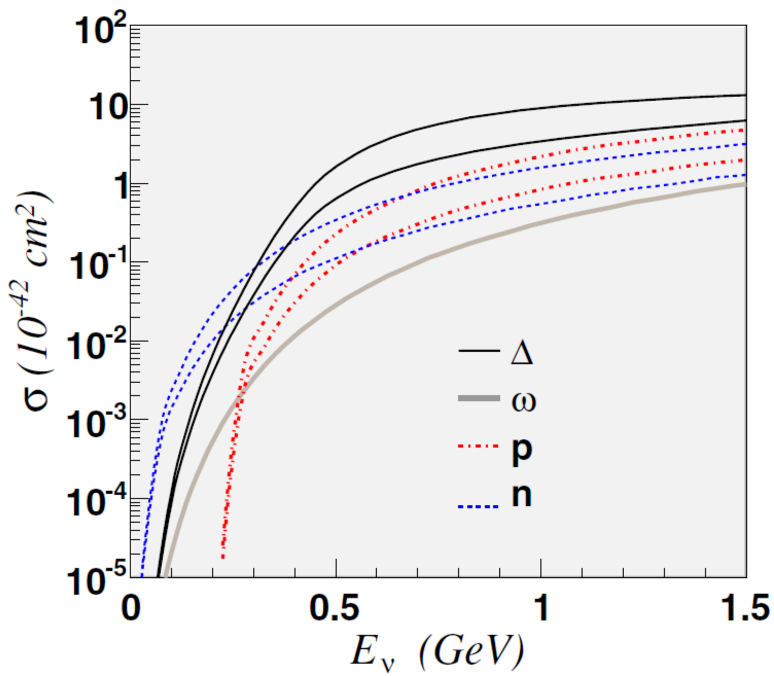
Quantity	Value
M_A	1.016 ± 0.026 GeV
$C_5^A(0)$	1.00 ± 0.11
$M_{A\Delta}$	0.93 ± 0.07 GeV
$A_{1/2}$	$(-140 \pm 6)10^{-3}$ GeV$^{-1/2}$
$A_{3/2}$	$(-265 \pm 5)10^{-3}$ GeV$^{-1/2}$
$a_{\rm HO}$	1.692 ± 0.015 fm
$\alpha_{\rm HO}$	1.082 ± 0.001 fm
$({\rm Im}\Sigma_\Delta)r$	$r = 1.0 \pm 0.1$



NCγ events at MiniBooNE

- Origin of e-like event excess @ MiniBooNE
  - Unaccounted backgrounds?
    - Higher order contributions
    - involve unknown constants, couplings
    - ω favored: large (uncertain) isoscalar ωNN coupling





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

R. Hill, PRD 81 (2010); 84 (2011)

- Very small

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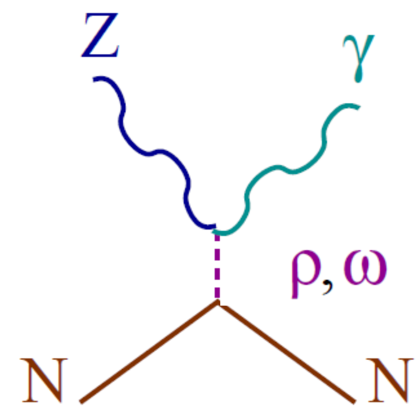

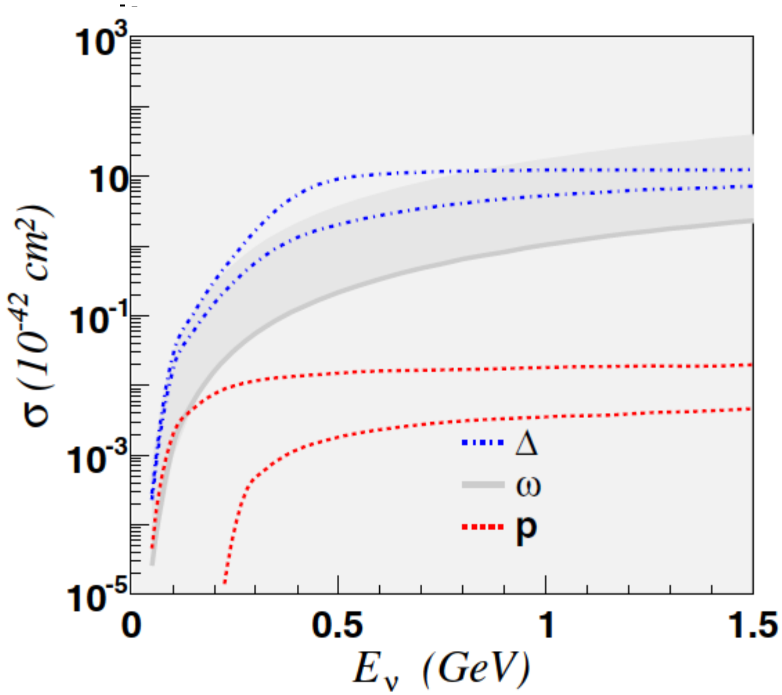

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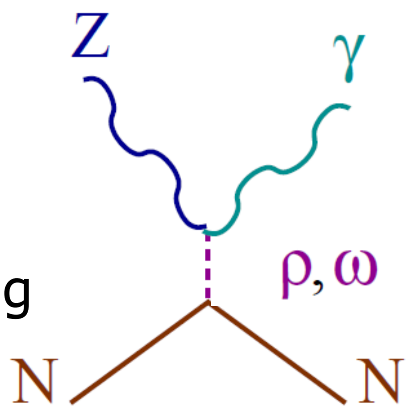
- Origin of e-like event excess @ MiniBooNE
  - Unaccounted backgrounds?
    - Higher order contributions
    - involve unknown constants, couplings
    - ω favored: large (uncertain) isoscalar ωNN coupling
    - Zhang & Serot
    - Contact terms:
      - negligible for E_ν < 550 MeV
      - rapidly growing with energy
      - Careful: unitarity bounds (loops)



NCγ events at MiniBooNE

- Origin of e-like event excess @ MiniBooNE
  - Unaccounted backgrounds? No

  - Multi-nucleon contributions
    - $Z\,NN \to NN\,\pi$, $Z\,NN \to NN\,\gamma$
    - Potentially important but unlikely to be the full solution

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)
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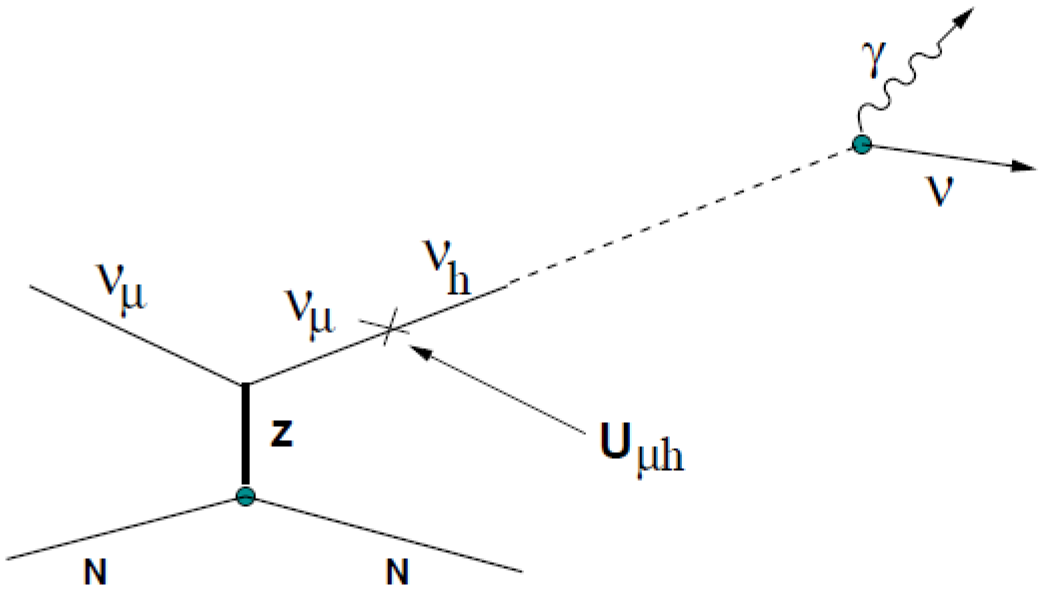

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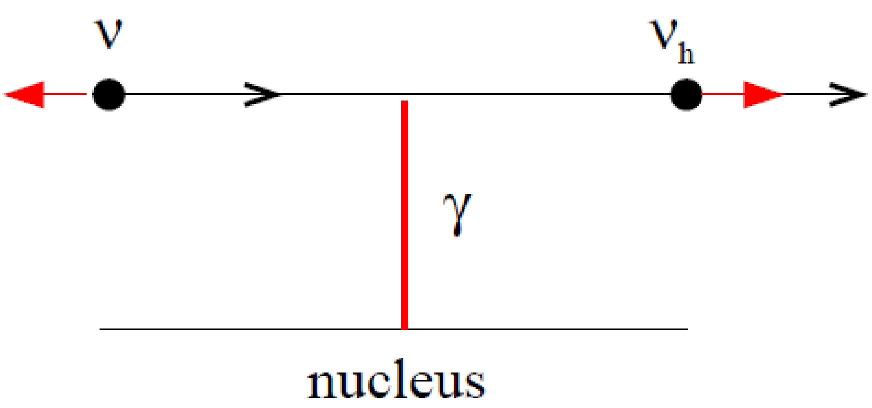
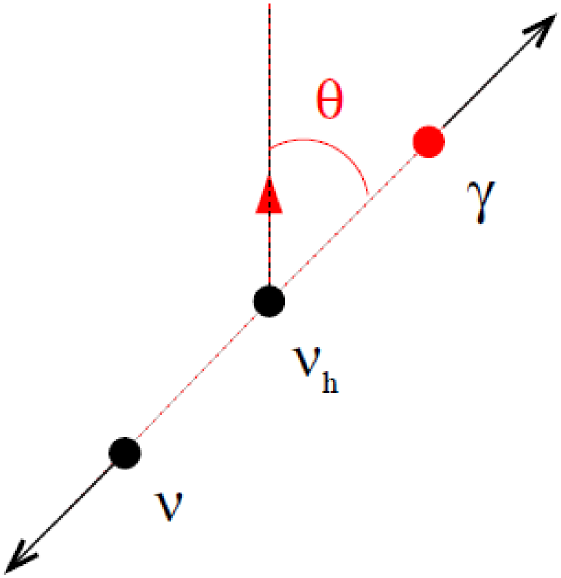




NCγ events at NOMAD

- Kullenberg et al., PLB 706 (2012)

$$\frac{\sigma(\mathrm{NC}\gamma)}{\sigma(\nu_\mu\, A \to \mu^-\, X)} < 4.0 \times 10^{-4} \quad \text{at 90 % CL}$$

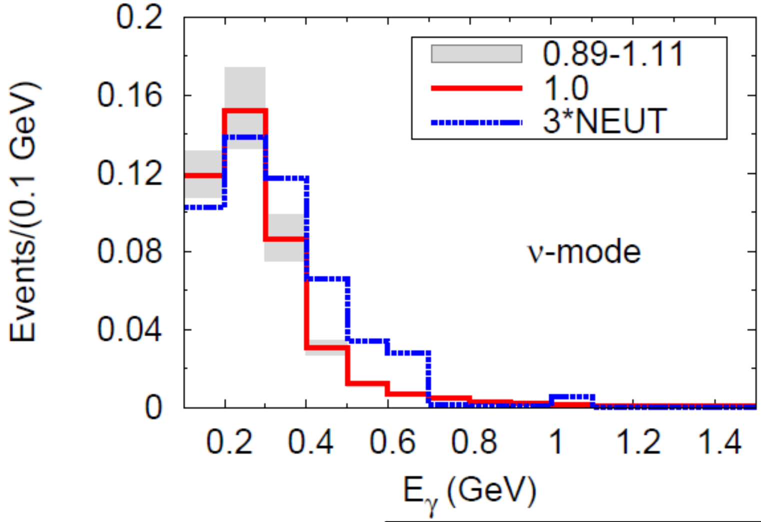
- Constraint to models attempting to explain the MiniBooNE anomaly (γ)
- In our case:
  - W γ_{N} < 1.6 GeV
  - Up to the extent that high q^2 extrapolations of the FF can be trusted
  - Neglecting nuclear effects

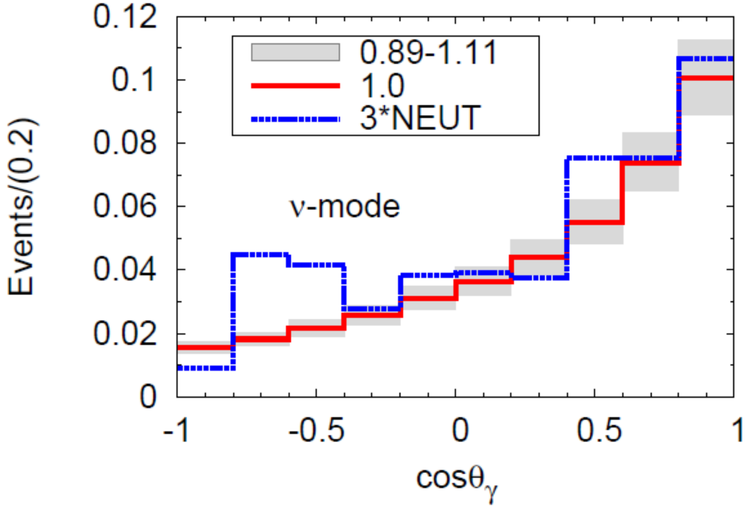
$$\frac{\sigma(\mathrm{NC}\gamma, W_{\gamma N} 1.6\,\mathrm{GeV})}{\sigma(\nu_\mu\, A \to \mu^-\, X)} \approx 0.8 \times 10^{-4} \quad \text{at } E_\nu = 25 \text{ GeV}$$

NCγ events at T2K

- Target: H_2O — Abe et al, PRL 112 (2014) 061802
- Mass: 22.5 ktons
- POT: 6.57×10^{20} (ν mode)
- Fluxes: SK250 100 MeV < E_ν < 3 GeV — Abe et al, PRD 87 (2013)
- No detection efficiency

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





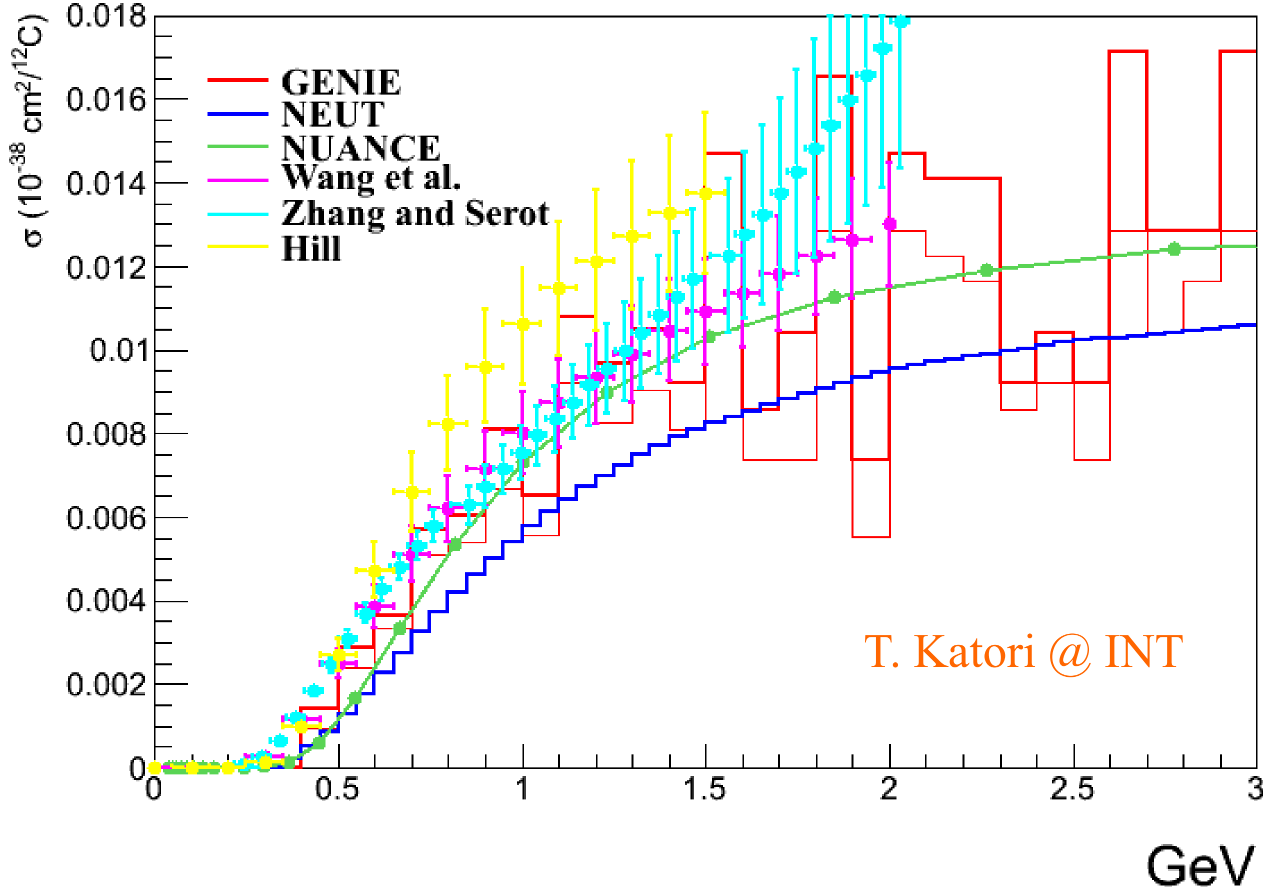
$N_{tot} = 0.421 \pm 0.051$ vs $N_{NEUT} = 0.165$

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

NCγ events at T2K

- Targ
- Mas
- POT
- Flux
- No c

- Com



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  - At least in part: YES
- Does this discrepancy matter?
  - For θ_{13}?: probably not.

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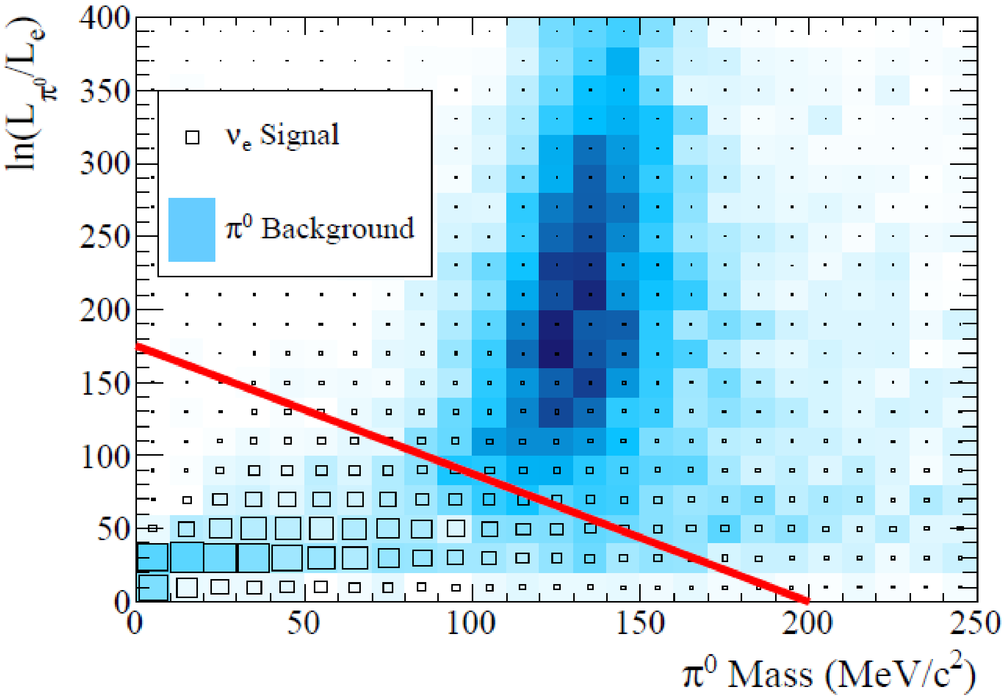

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- Comparison tc ... imate

$$N_{tot} = 0.4$$

- Does this disc ... l. cross sections?
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  - Better π^0 rejection cut ⇒ NCγ relatively more important

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  - Better π^o rejection cut $\Rightarrow$ NCγ relatively more important
- For CP violation searches? perhaps…

Conclusions

- We have studied photon emission induced by NC interactions with nucleons and nuclei at $E_\nu \sim 1$ GeV
- Reaction dominated by $\Delta(1232)$ 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 (in line with Zhang, Serot, PLB 719).
- NCγ : insufficient to explain the excess of e-like events at MiniBooNE
- Implications for T2K discussed: 2.5 more NCγ events predicted.
- NOMAD limit respected
- Details in:
  - E. Wang, LAR, J. Nieves, PRC 89 (2014) 015503
  - E. Wang, LAR, J. Nieves, arXiv:1407.6060