Photon Emission in NC interactions

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

Introduction

- Single Photon emission in NC interactions:
  - E. Wang, LAR, J. Nieves, PRC 89 (2014) 015503 https://doi.org/10.1016/j.physletb.2014.11.025
  - E. Wang, LAR, J. Nieves, PLB 740 (2015) 16 https://doi.org/10.1016/j.physletb.2014.11.02
  - E. Wang, LAR, Y. Hayato, K. Mahn, J. Nieves, PRD92 (2015) 053005 https://doi.org/10.1103/PhysRevD.92.053005
  - LAR, J. Nieves, E. Saúl Sala, E. Wang, J. Phys. Conf. Ser. 1056 (2018) 012001 https://doi.org/10.1088/1742-6596/1056/1/012001

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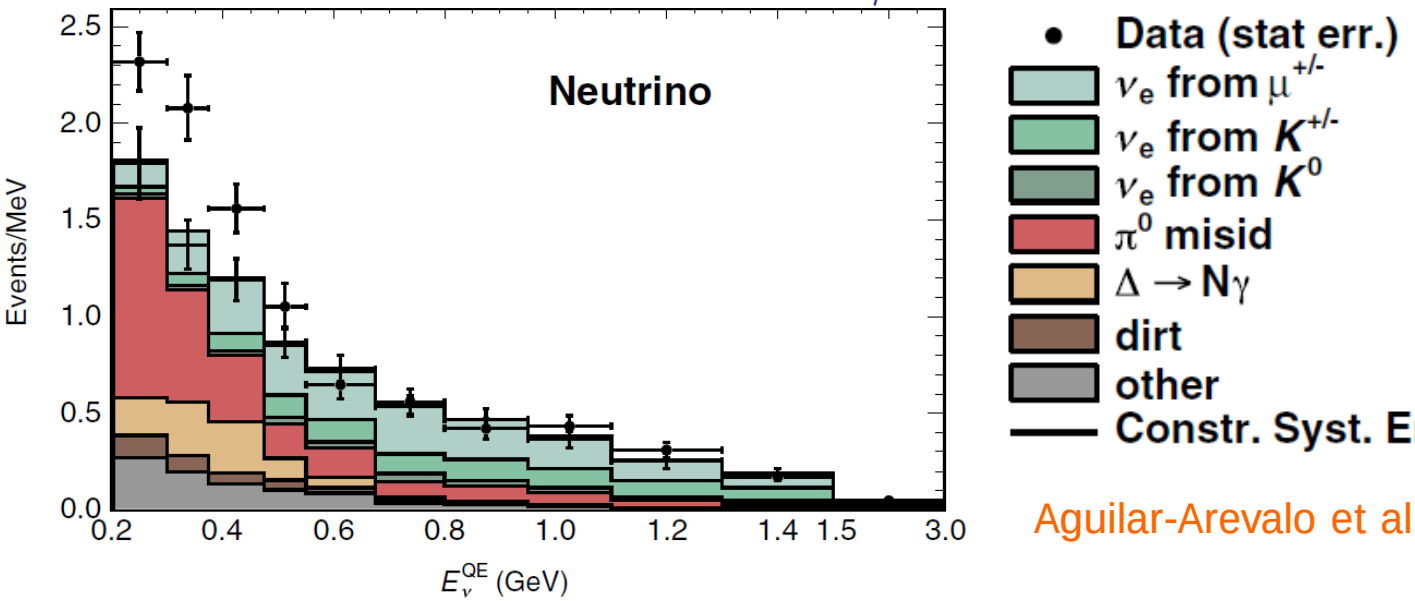
  - Ongoing MicroBooNE analysis: Public note 1041, http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1041-PUB.pdf

Introduction

- Single Photon emission in NC interactions:
  - 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 $\nu_\mu \rightarrow \nu_e$ search:



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

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

Introduction

- Single 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

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In GENIE:

$\Delta \rightarrow$ N γ decay

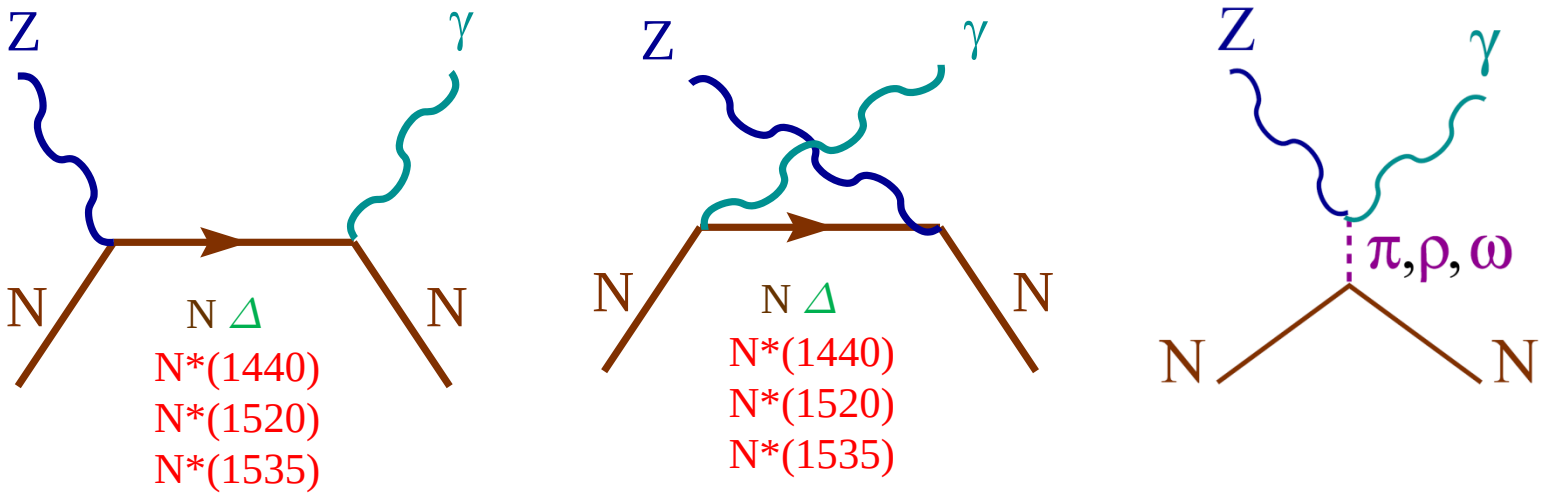
+ global Fermi gas

not available

E. Saúl Sala, S. Dytman, ...

The model

- Feynman diagrams:

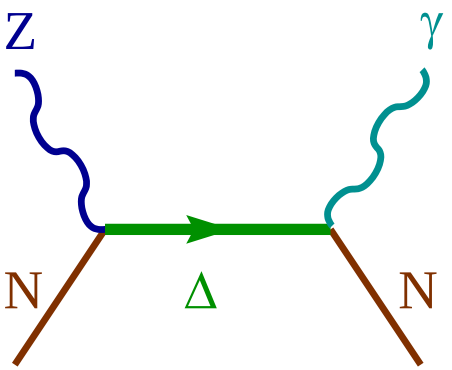


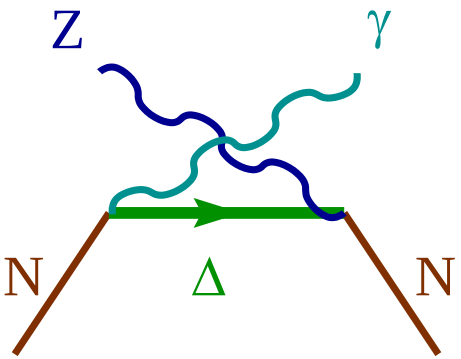
R. Hill, PRD 81 (2010)
Zhang & Serot, PRC 86 (2012)
Wang, LAR, Nieves, PRC 89 (2014)

The model

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

- $\Delta(1232)$ pole terms:





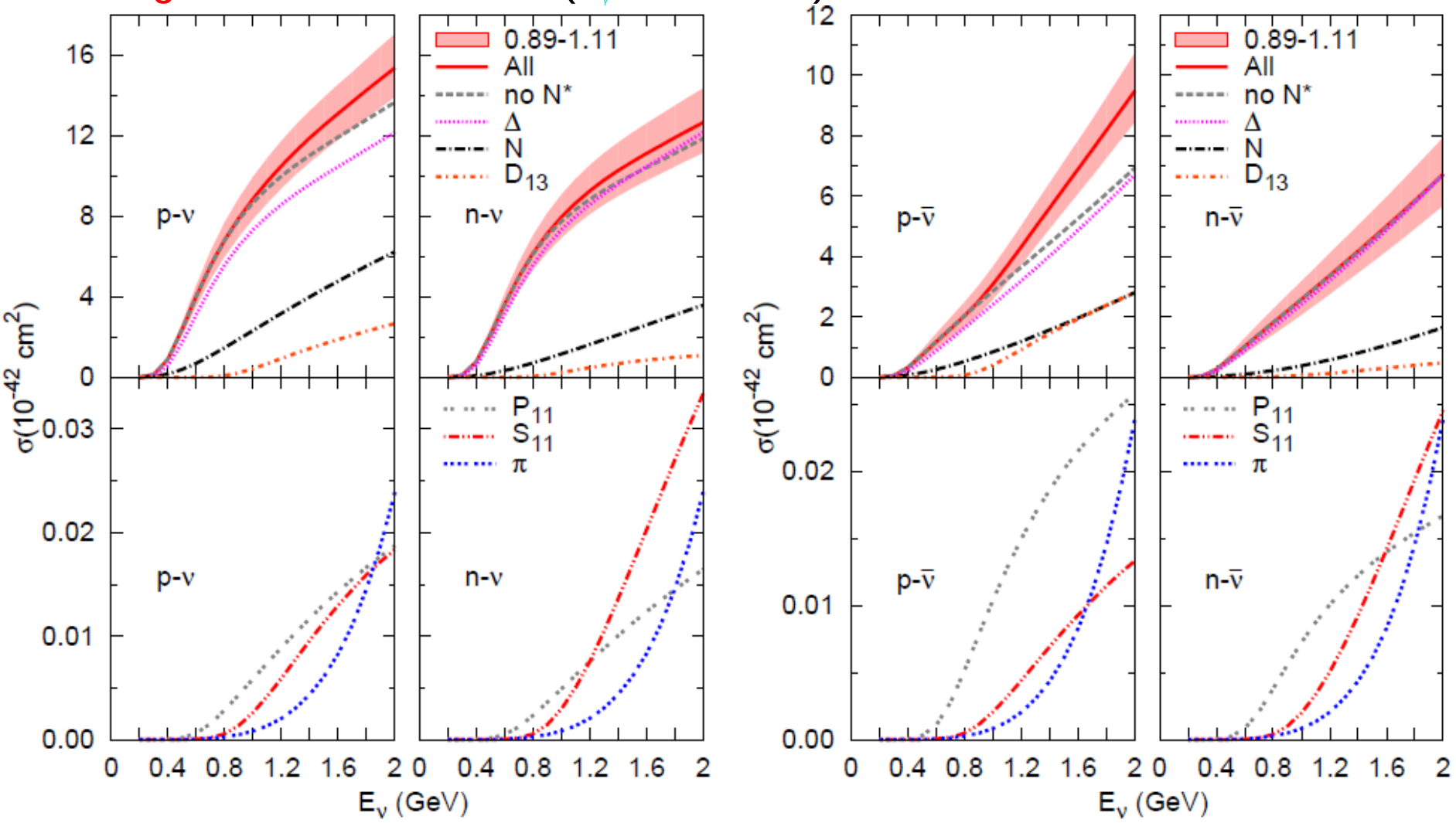
$$\Gamma^{\mu\alpha} = \hat{J}^{\delta\mu}_{\rm EM}(p', q_\gamma) D^{\Delta}_{\delta\sigma}(p+q) J^{\sigma\alpha}_{\rm NC}(p,q) + \hat{J}^{\delta\alpha}_{\rm NC}(p', -q) D^{\Delta}_{\delta\sigma}(q_\gamma - p) J^{\sigma\mu}_{\rm EM}(p', -q_\gamma)$$

$$J^{\beta\mu}_{\rm NC}(p,q) = \left[\frac{\tilde{C}_3^V(q^2)}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{\tilde{C}_4^V(q^2)}{M^2}(g^{\beta\mu} q\cdot p_\Delta - q^\beta p_\Delta^\mu) + \frac{\tilde{C}_5^V(q^2)}{M^2}(g^{\beta\mu} q\cdot p - q^\beta p^\mu)\right]\gamma_5$$
$$+ \frac{\tilde{C}_3^A(q^2)}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{\tilde{C}_4^A(q^2)}{M^2}(g^{\beta\mu} q\cdot p_\Delta - q^\beta p_\Delta^\mu) + \tilde{C}_5^A(q^2) g^{\beta\mu}$$

$$J^{\beta\mu}_{\rm EM}(p,q_\gamma) = \left[\frac{C_3^{(p,n)}(0)}{M}(g^{\beta\mu}\not{q}_\gamma - q_\gamma^\beta\gamma^\mu) + \frac{C_4^{(p,n)}(0)}{M^2}(g^{\beta\mu} q_\gamma\cdot p_\Delta - q_\gamma^\beta p_\Delta^\mu) + \frac{C_5^{(p,n)}(0)}{M^2}(g^{\beta\mu} q_\gamma\cdot p - q_\gamma^\beta p^\mu)\right]\gamma_5$$

Results on nucleons

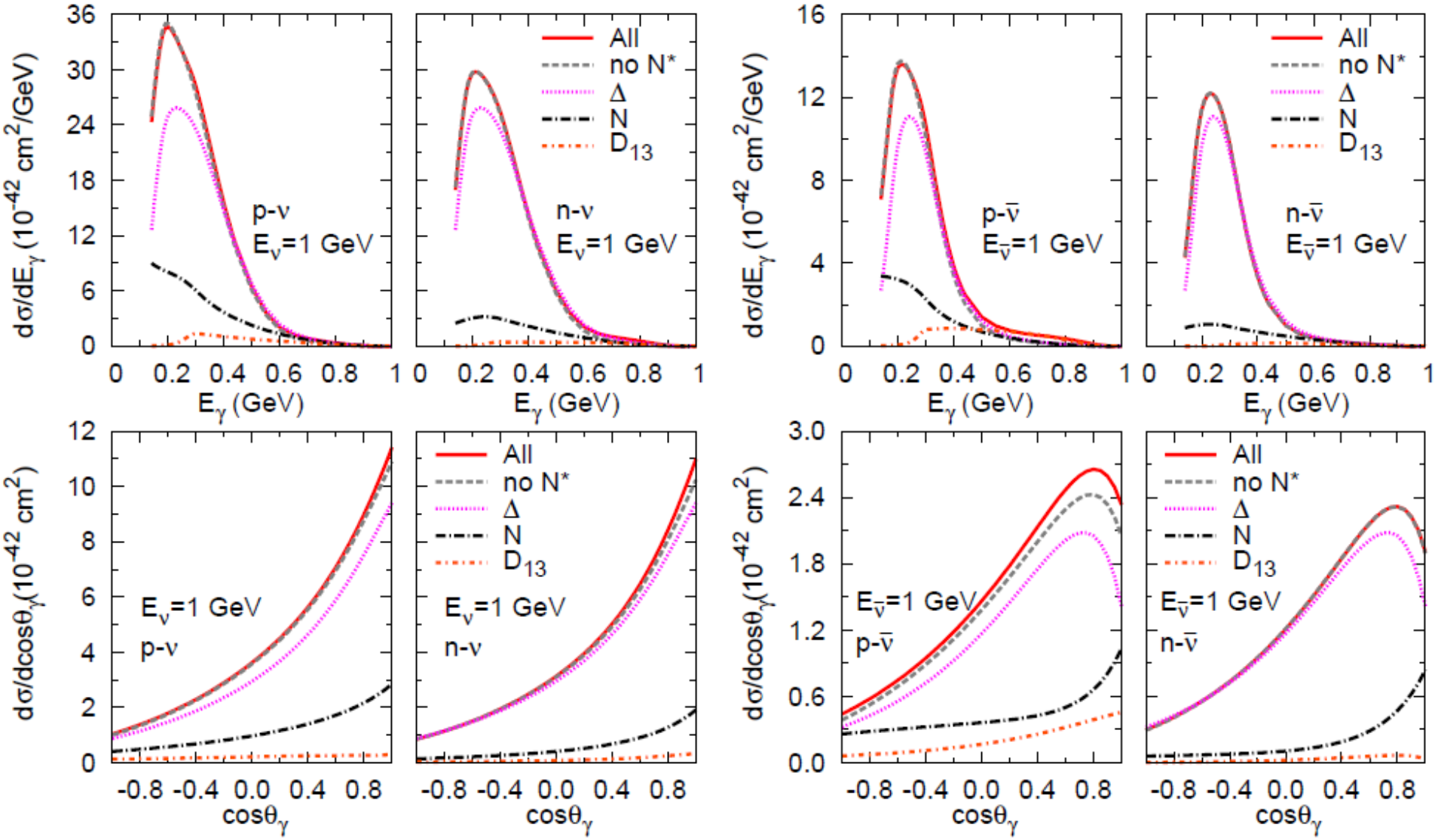
- Integrated cross sections ($E_\nu > 140$ MeV)



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

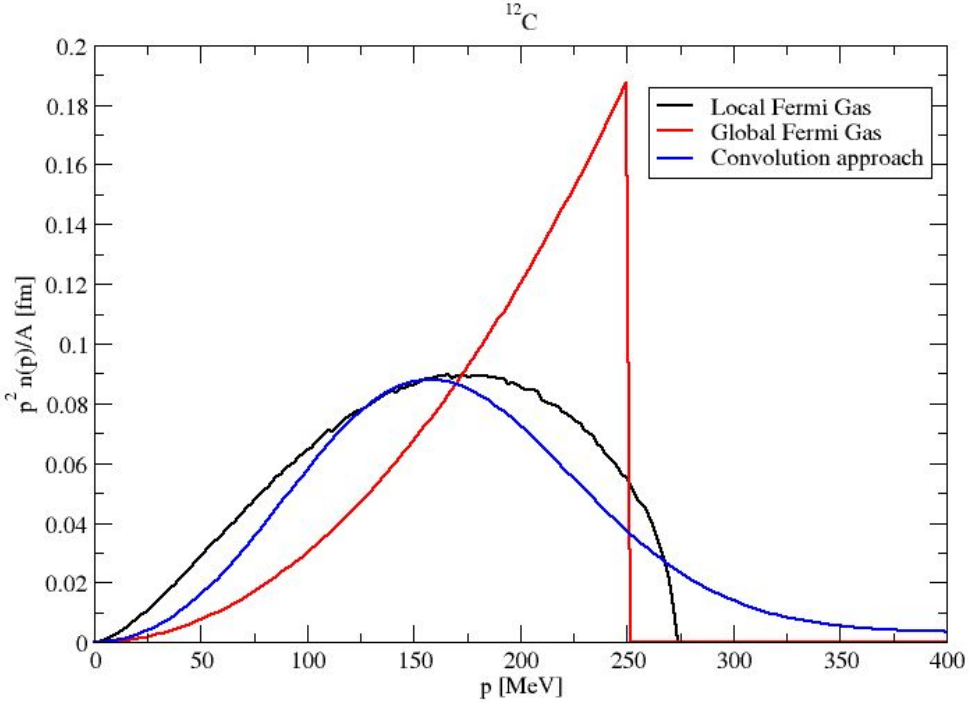
Results on nucleons

- Differential cross sections at E_ν = 1 GeV (E_γ > 140 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 $P_{\rm Pauli} = 1 - \Theta(p_F(r) - |\vec{p}|)$
- Free nucleons but with space-momentum correlations absent in the GFG



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

Nuclear effects

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

replace $M_\Delta \rightarrow M_\Delta + \mathrm{Re}\Sigma_\Delta(\rho)$

$\dfrac{\Gamma_\Delta}{2} \rightarrow \dfrac{\tilde{\Gamma}_\Delta(\rho)}{2} - \mathrm{Im}\Sigma_\Delta(\rho)$

$\tilde{\Gamma}_\Delta \leftarrow$ Free width $\Delta \rightarrow$ N π modified by Pauli blocking

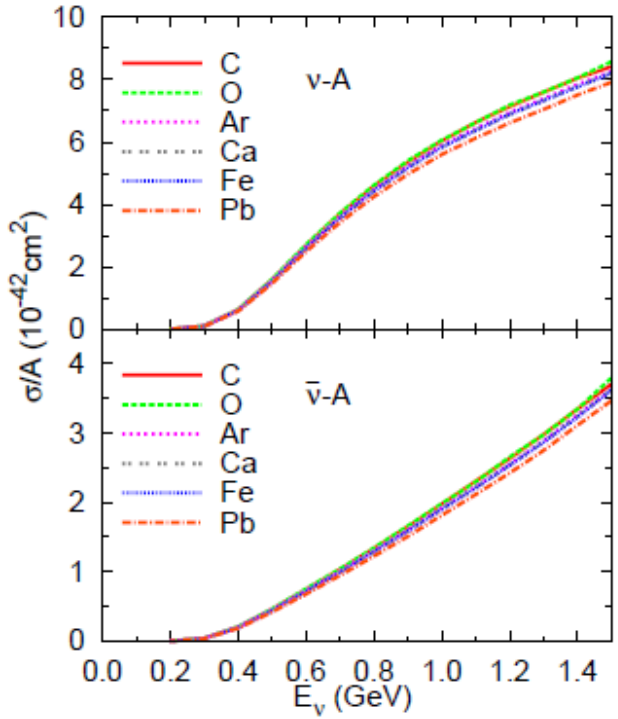
$\mathrm{Re}\Sigma_\Delta(\rho) \approx 0$

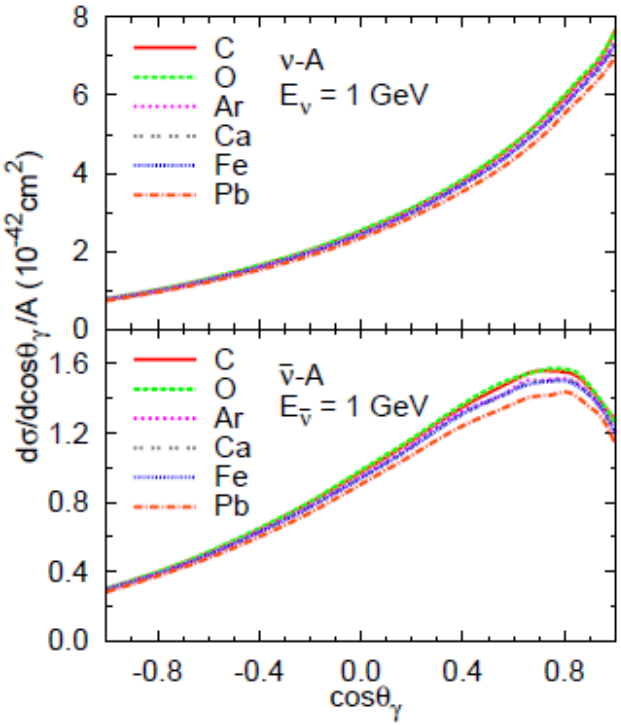
$\mathrm{Im}\Sigma_\Delta(\rho) \leftarrow$ many-body processes:

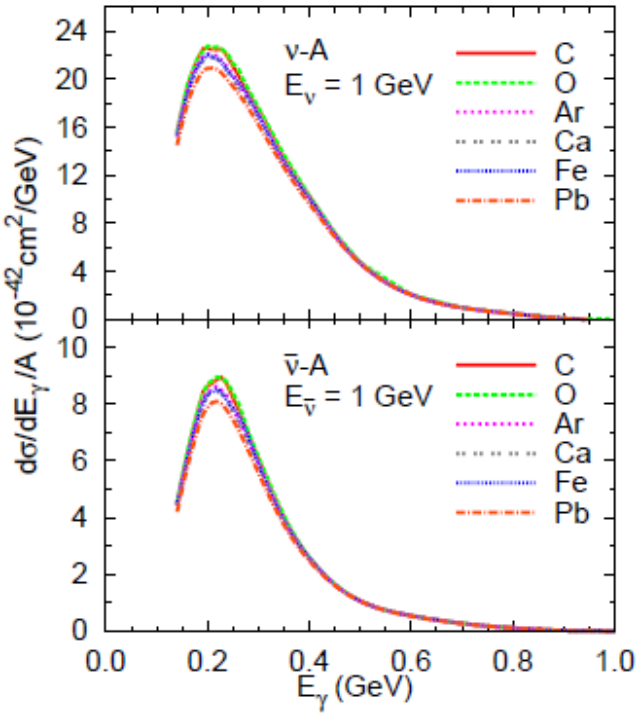
- Δ N $\rightarrow$ N N
- Δ N $\rightarrow$ N N π
- Δ N N $\rightarrow$ N N N

Results

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

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

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

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

Results

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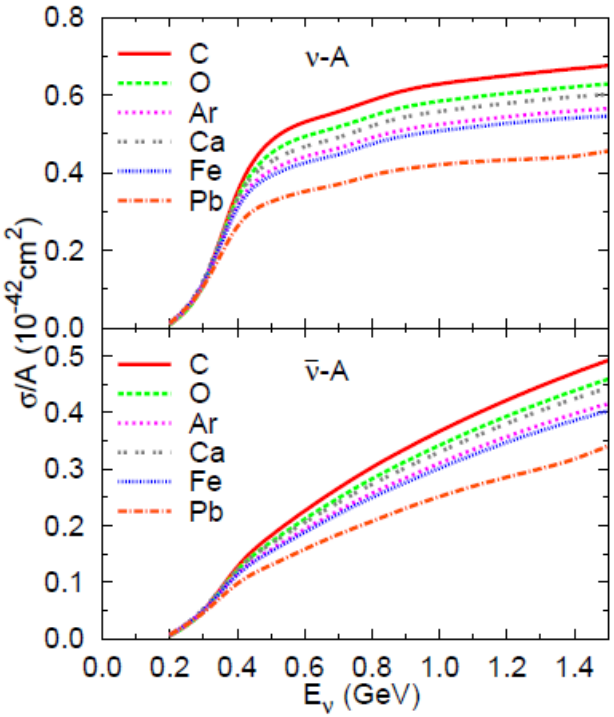
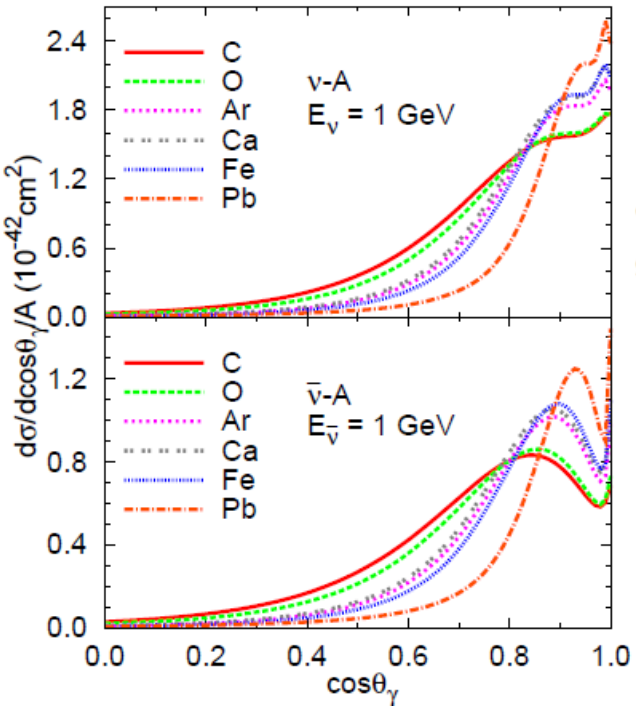
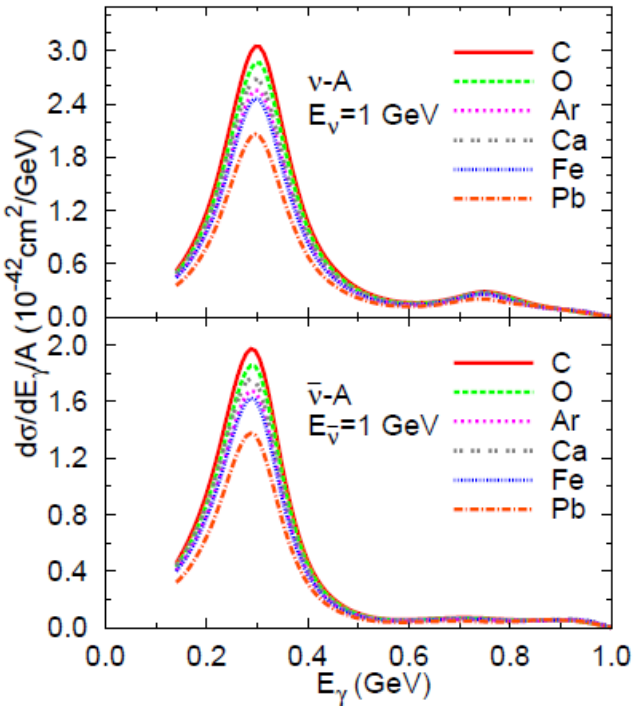
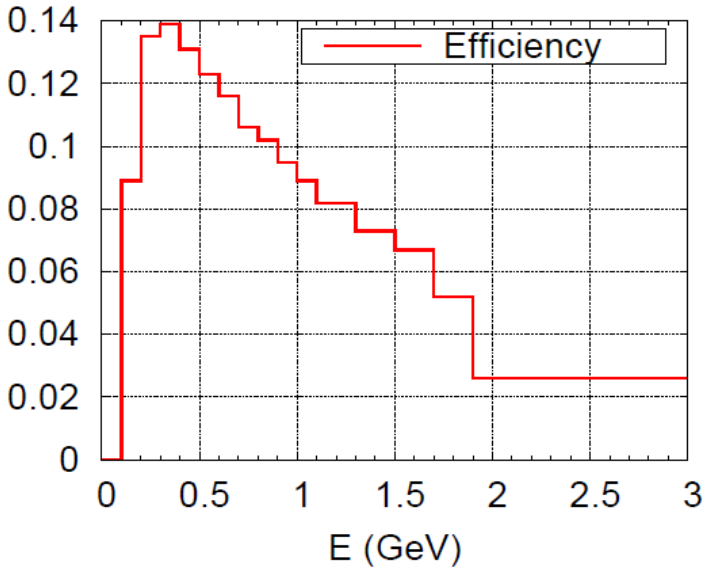






NCγ events at MiniBooNE

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



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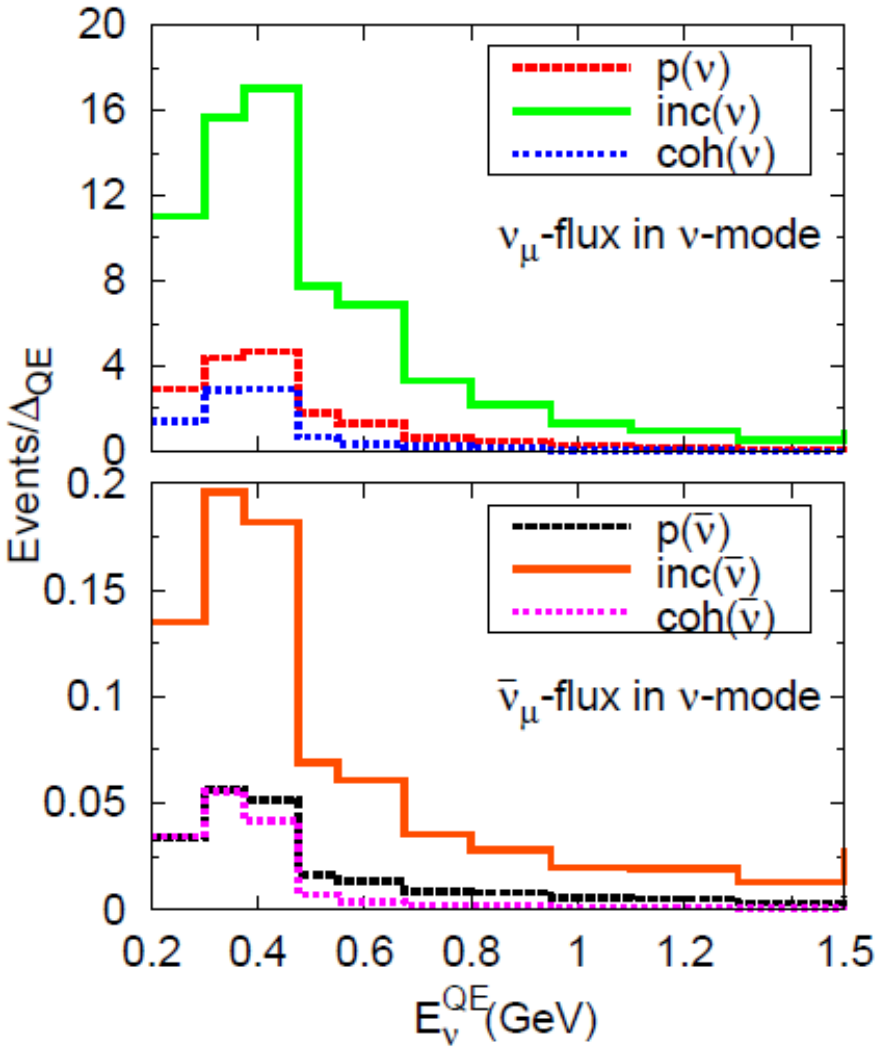

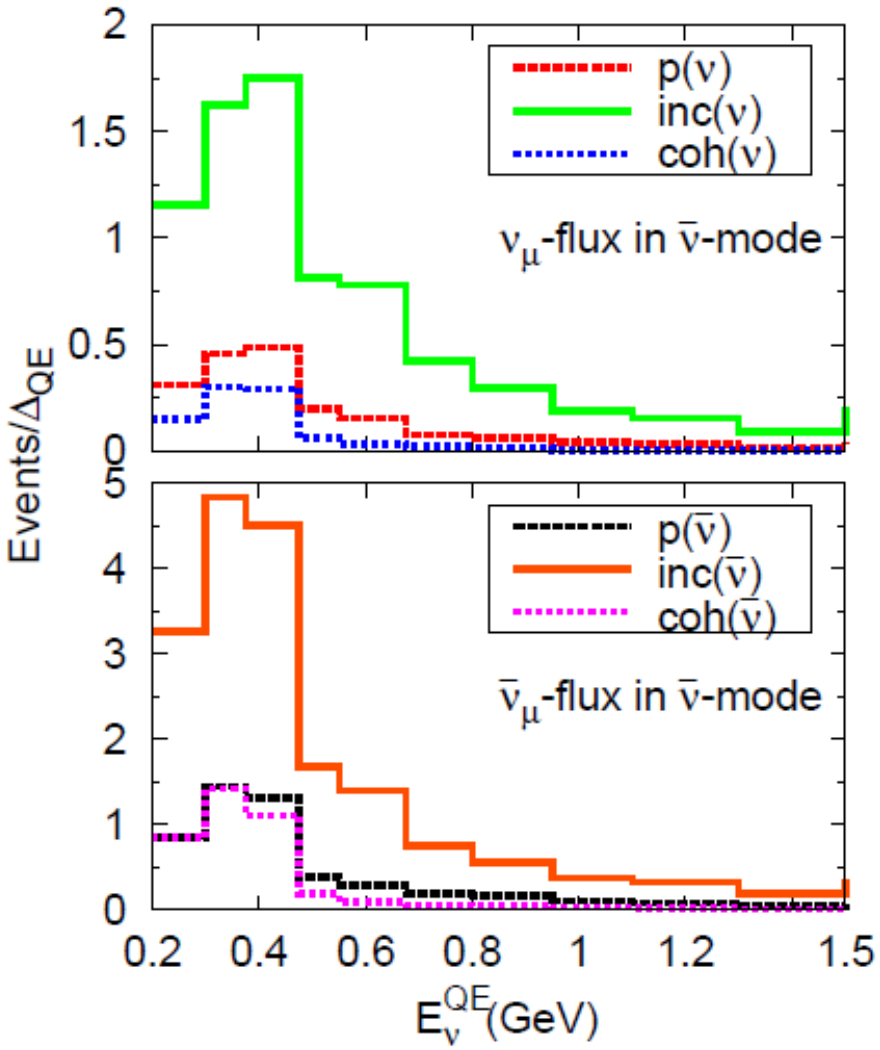

- 30-40 % of ν induced events in $\bar{\nu}$ mode

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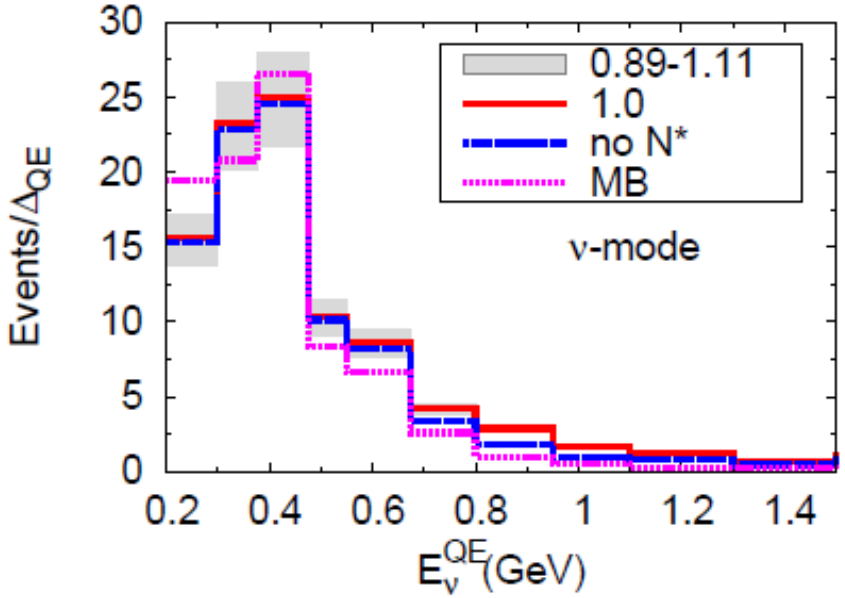

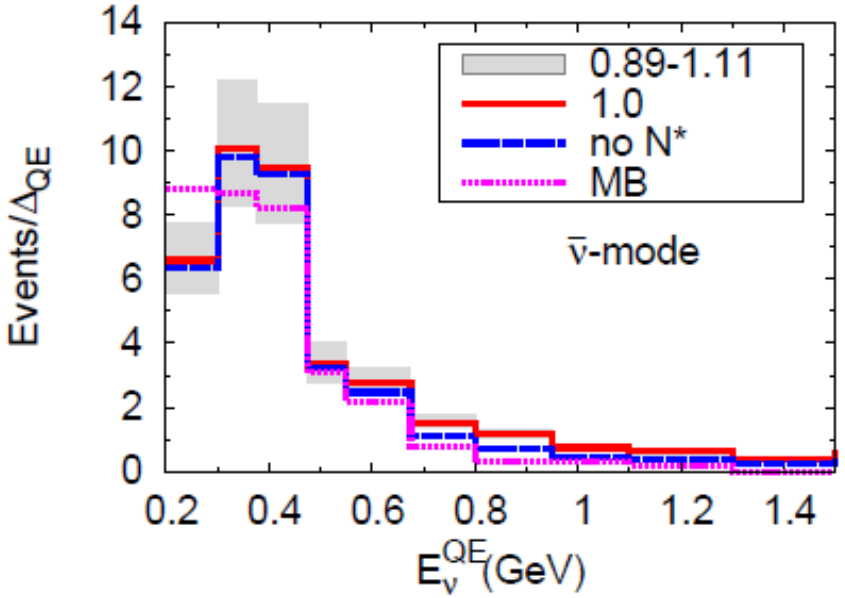

E. Wang, LAR, J. Nieves, PLB 740 (2015)

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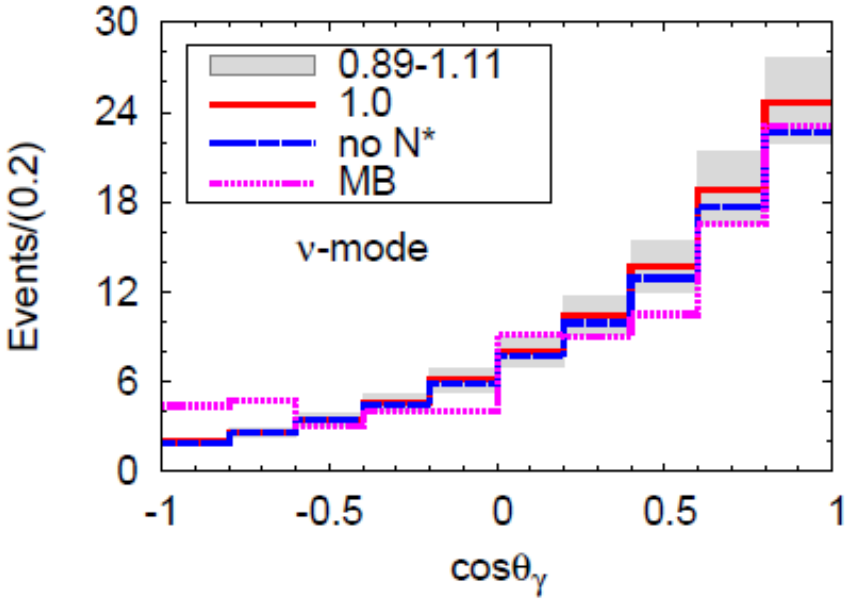

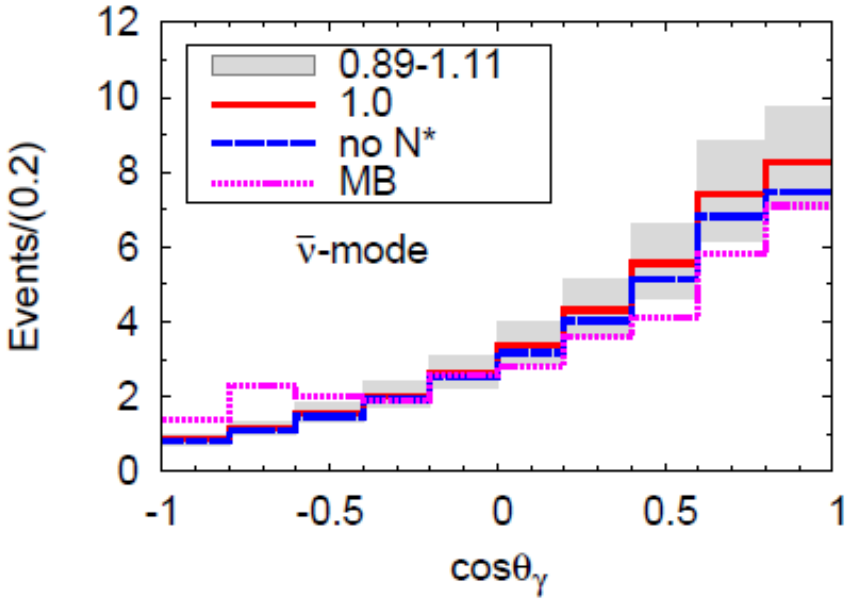

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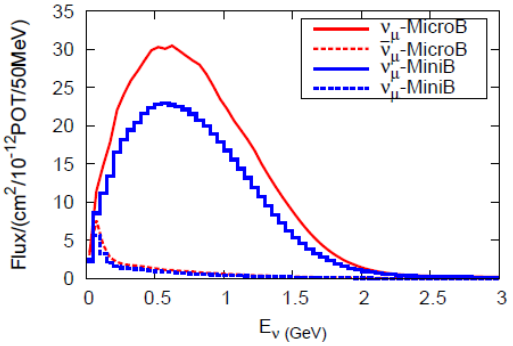
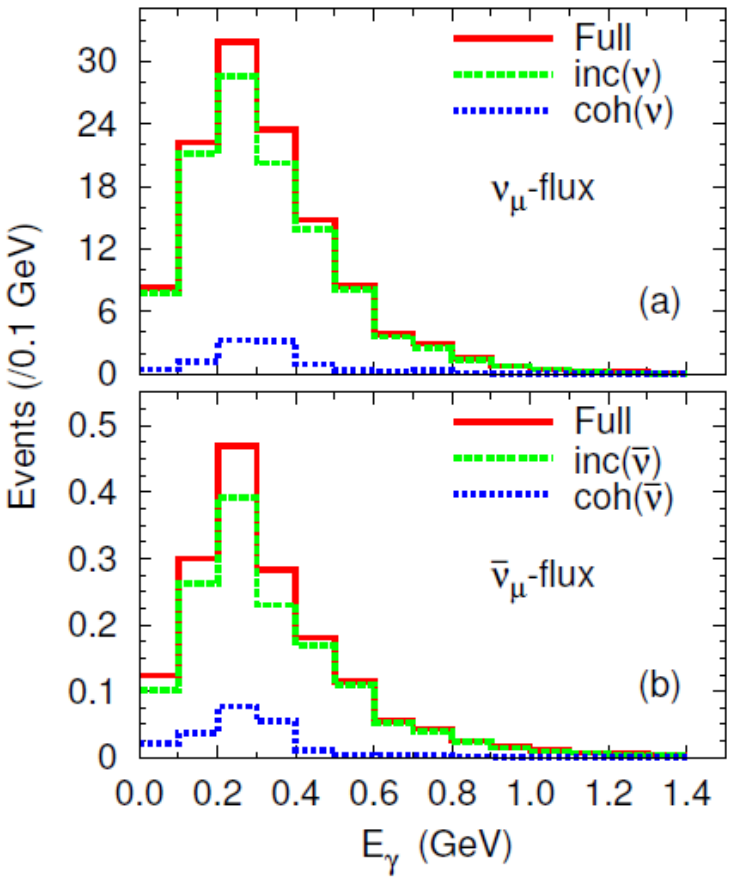
- Comparison to the MiniBooNE estimate
  - NCγ : insufficient to explain the excess of e-like events at MiniBooNE
  - Same conclusion as Zhang, Serot, PLB 719 (2013)

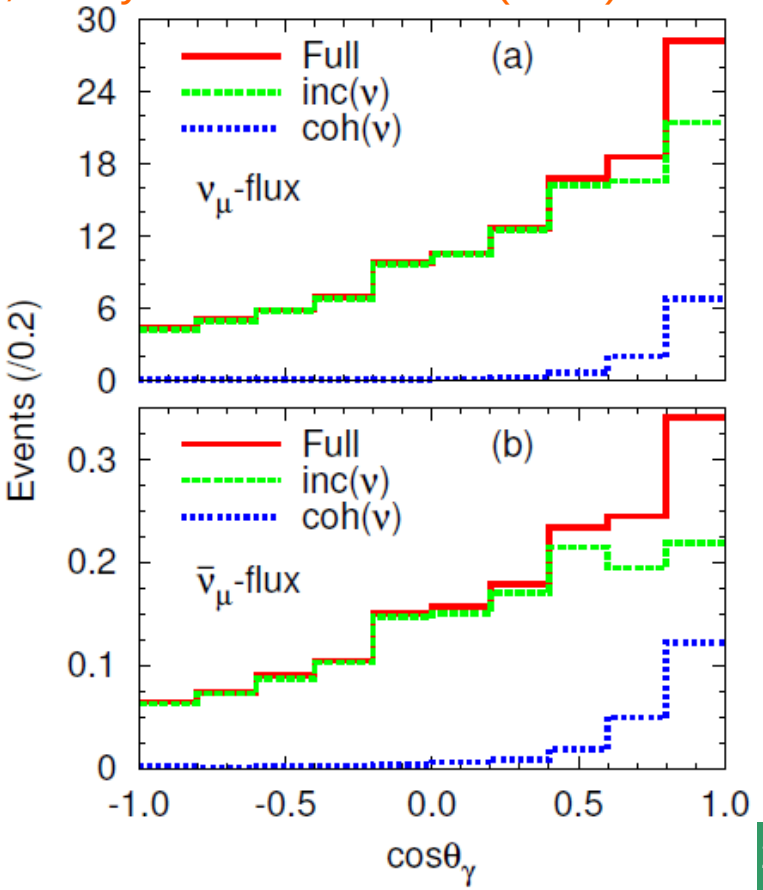
MicroBooNE

- 6.6×10^{20} POT
- Active mass = 86.6 tons
- Flux prediction:



LAR, J. Nieves, E. Saúl Sala, E. Wang, J. Phys. Conf. Ser. 1056 (2018)





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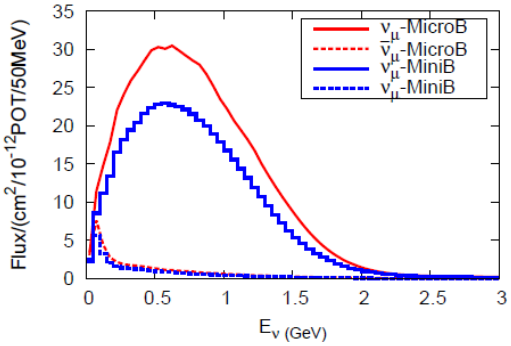
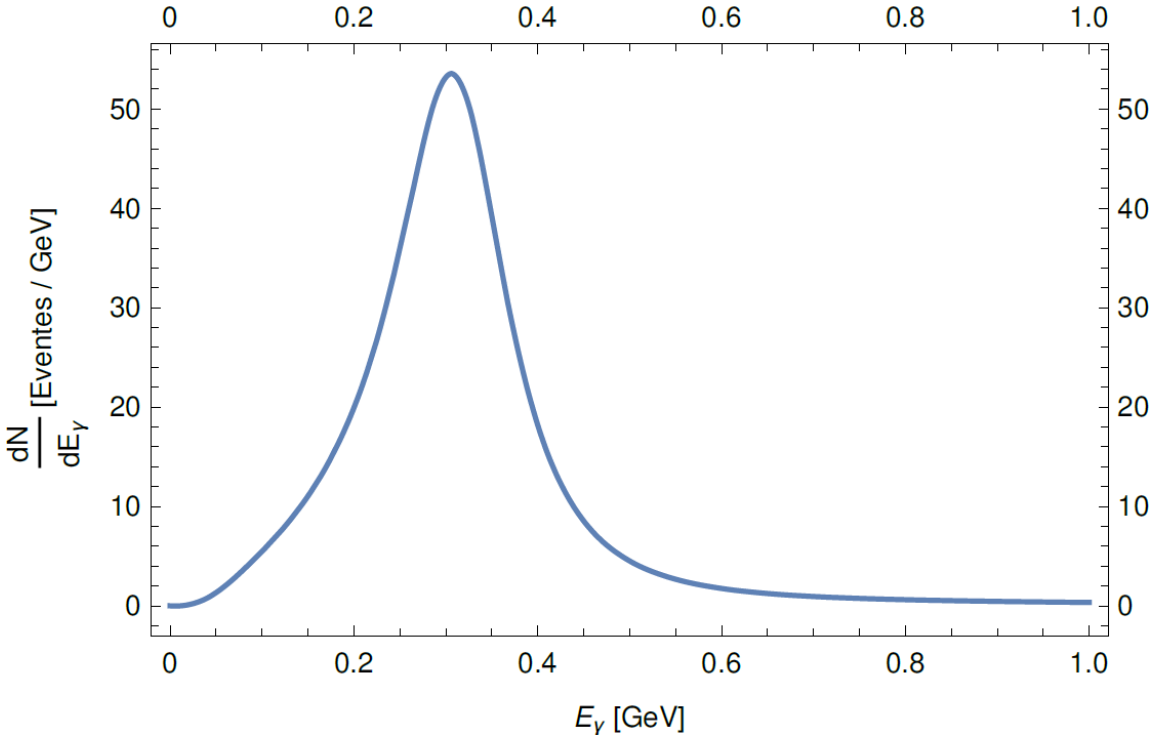


- Coherent channel: E. Saúl Sala, LAR



Summary

- 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
- NCγ : insufficient to explain the excess of e-like events at MiniBooNE
- Predictions for MicroBooNE

Ideas

- At MicroBooNE , $\Delta \rightarrow$ N γ should be large, with some non-resonant contribution.
- Comparisons of our results vs GENIE may helpful for the analysis.
- It is important to have a coherent NCγ in GENIE.
- Could NC(γ+p) be an easier/cleaner measurement?

- NC2γ background to NCγ
  - NCπ^o (tension between MiniBooNE and MINERvA pion measurements)
  - NCη : how relevant? We have observed some differences vs GENIE.

Ideas

- Alam, LAR, Athar, Vicente Vacas, preliminary