Photon Emission in NC interactions

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

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Introduction

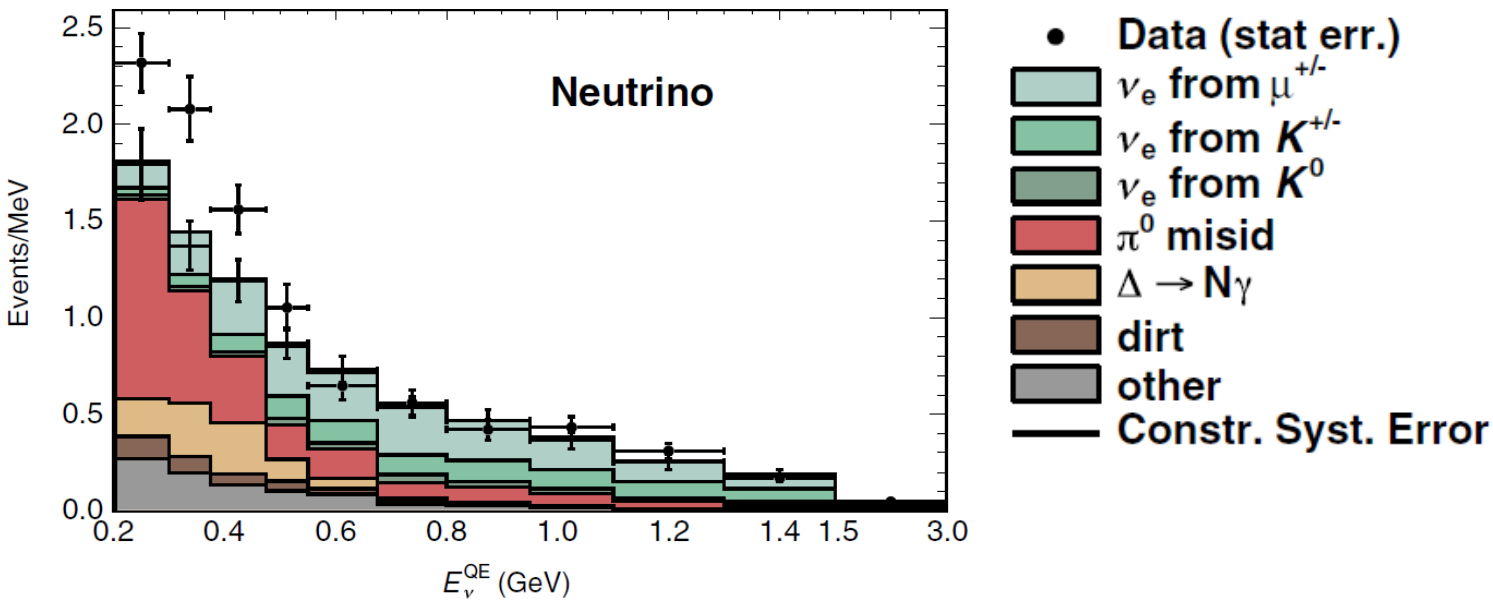
- Photon emission in NC interactions:
  - on nucleons $\nu(\bar{\nu})\, N \rightarrow \nu(\bar{\nu})\, \gamma\, N$
  - on nuclei $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, X$ $\leftarrow$ incoherent

    $\nu(\bar{\nu})\, A \rightarrow \nu(\bar{\nu})\, \gamma\, A$ $\leftarrow$ coherent
  - 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 $\bar{\nu}_e\, p \rightarrow e^+\, n$

Introduction

- 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 $\leftarrow$ largest background
  - NC $\Delta \rightarrow N\gamma \leftarrow$ 2nd largest background: determined from the number of measured NC π^o events

Introduction

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

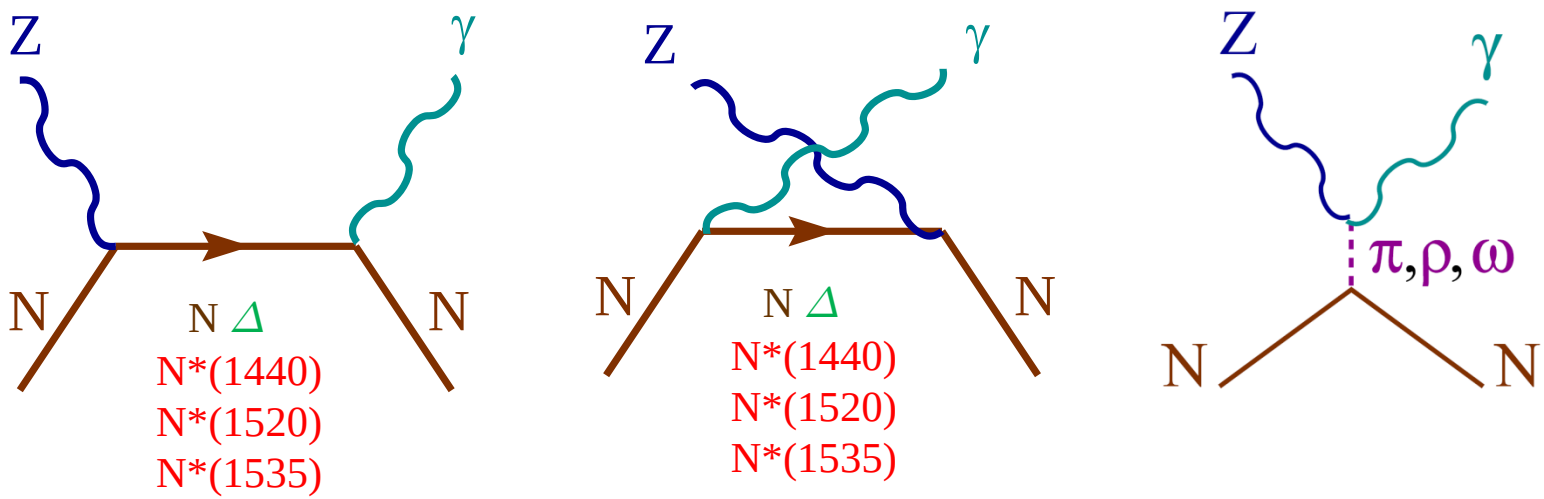
  ... but some are more constrained than others.

  - NC π^o
    - measured @ MiniBooNE
    - Rein-Sehgal resonance production model + non-resonant background
    - π FSI

  - NC $\Delta \rightarrow$ N γ
    - relies on the determination of weak N-R vertices
    - No background
    - No coherent channel

The model

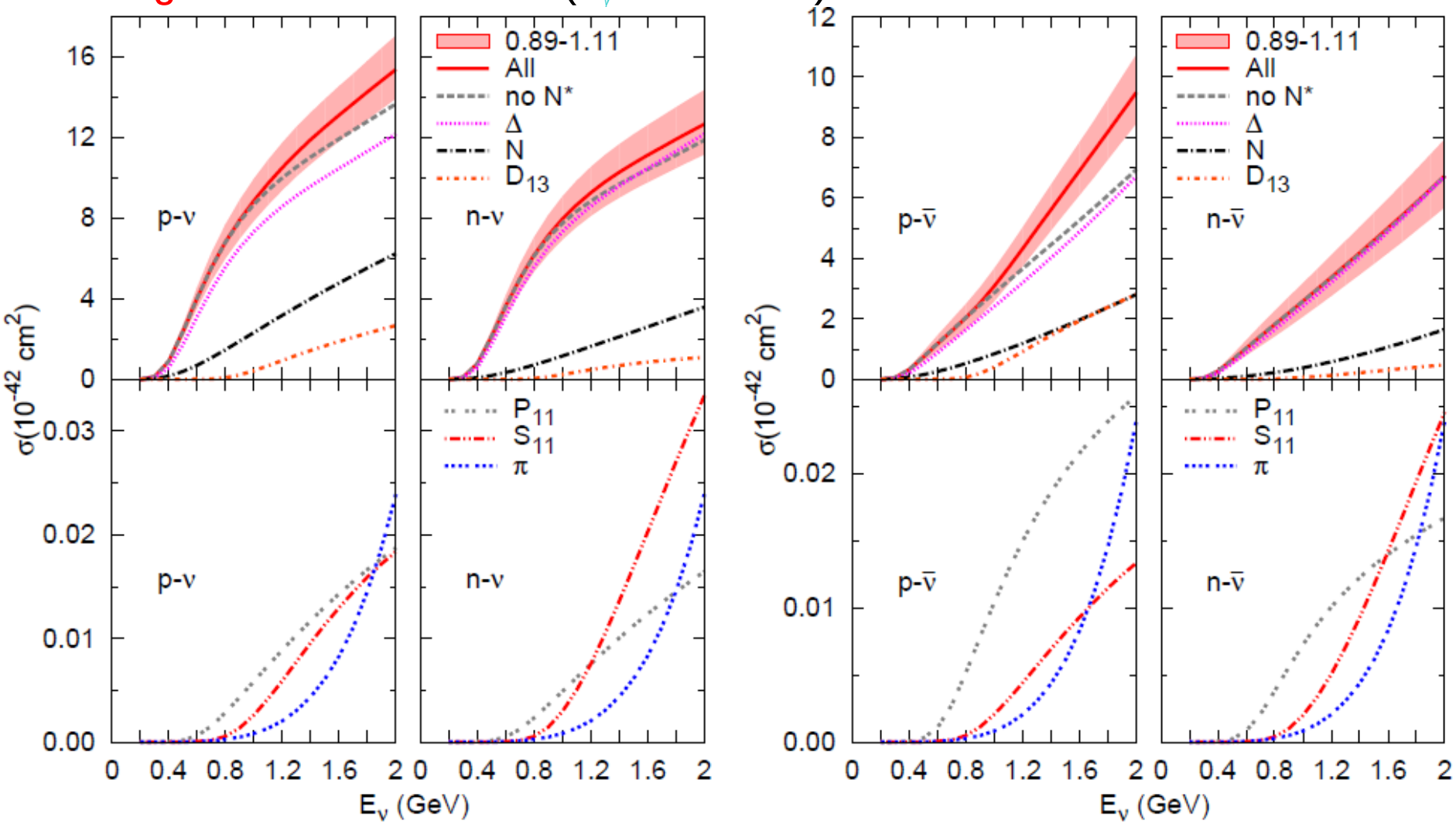
- Feynman diagrams:



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

Results on nucleons

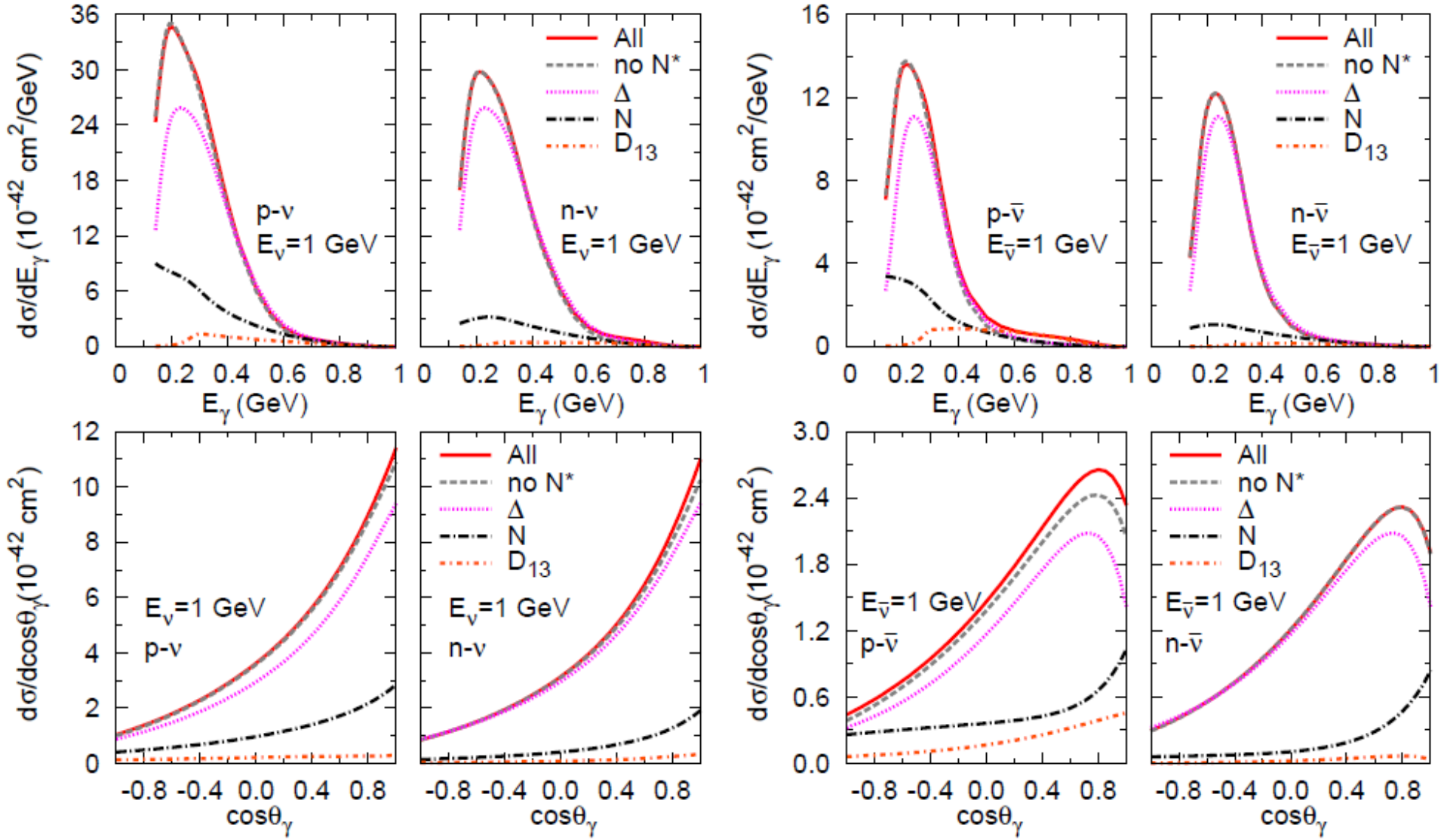
- Integrated cross sections ($E_\nu > 140$ MeV)



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

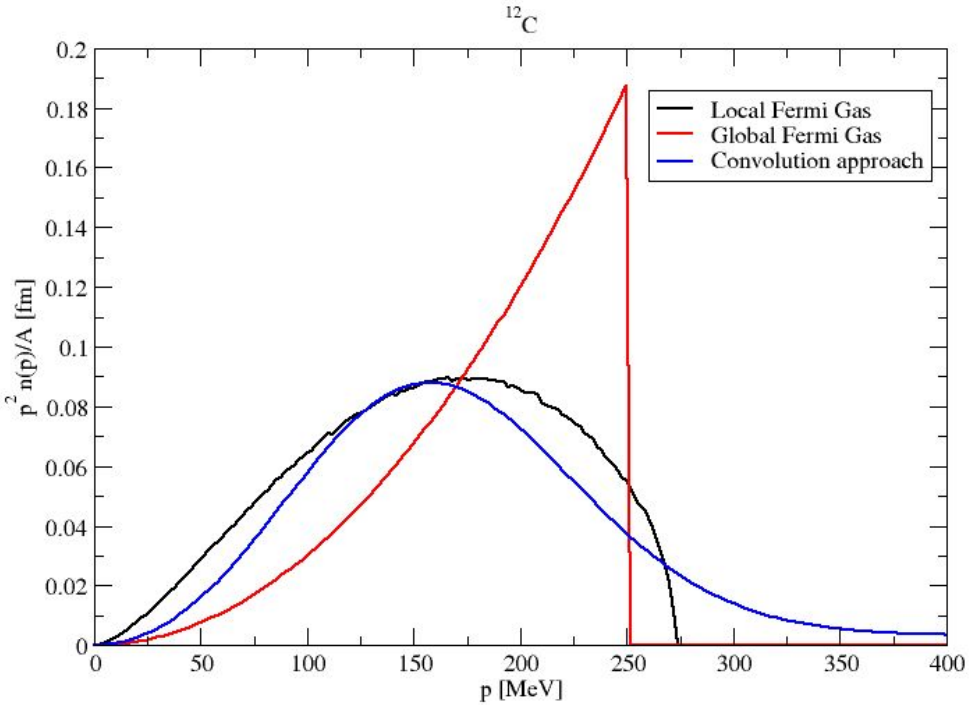
Results on nucleons

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



Nuclear effects

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

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

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

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

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

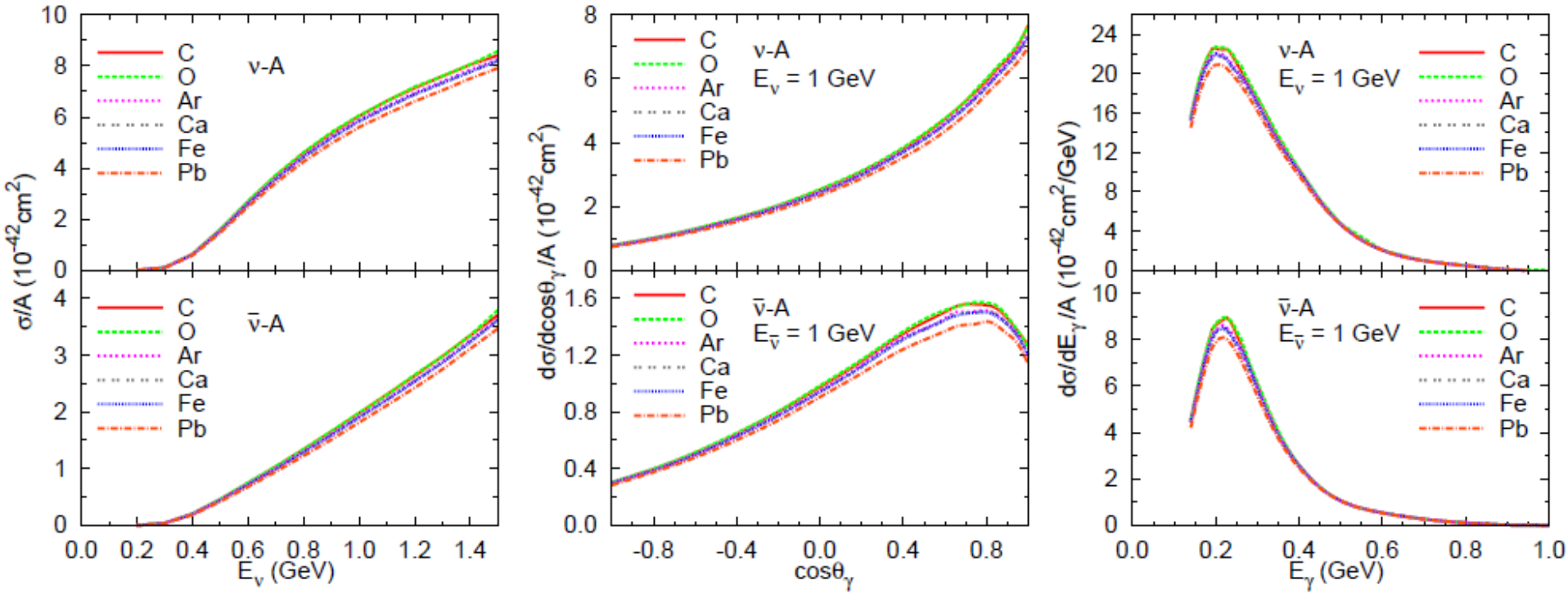
$\mathrm{Im}\Sigma_\Delta(\rho) \leftarrow$ many-body processes:

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

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

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

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

Results

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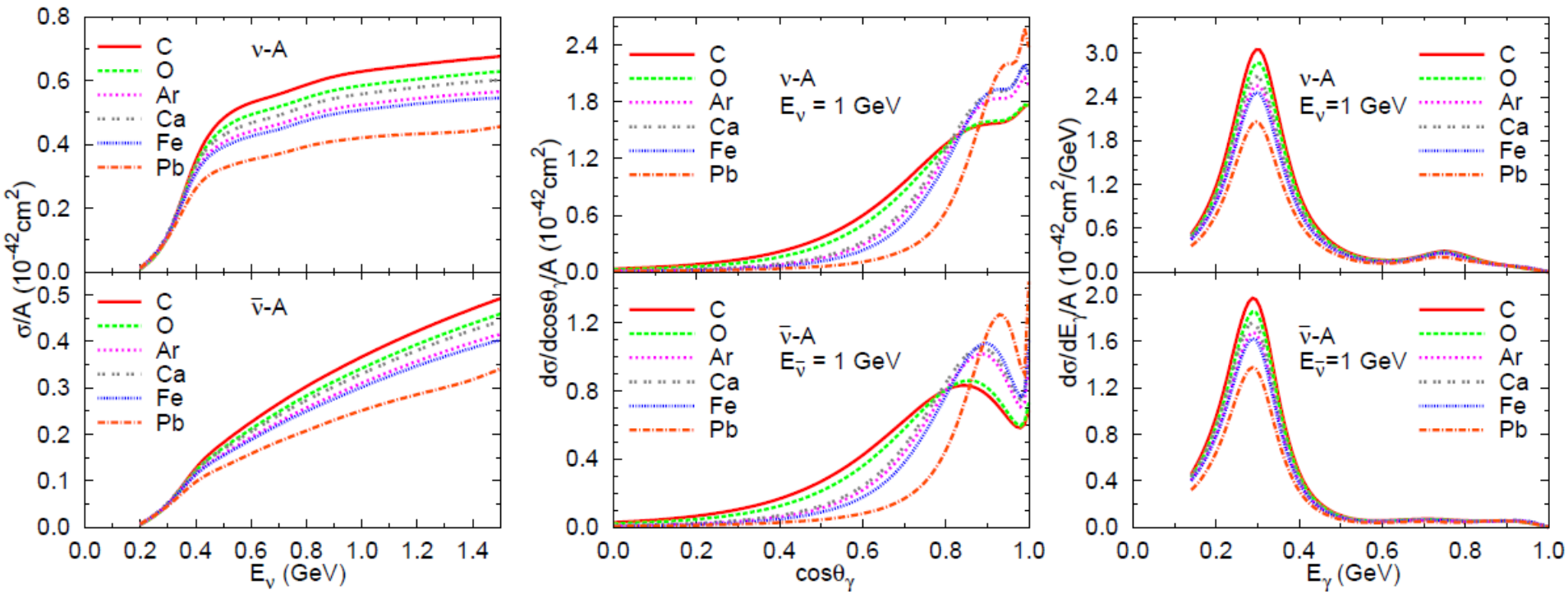
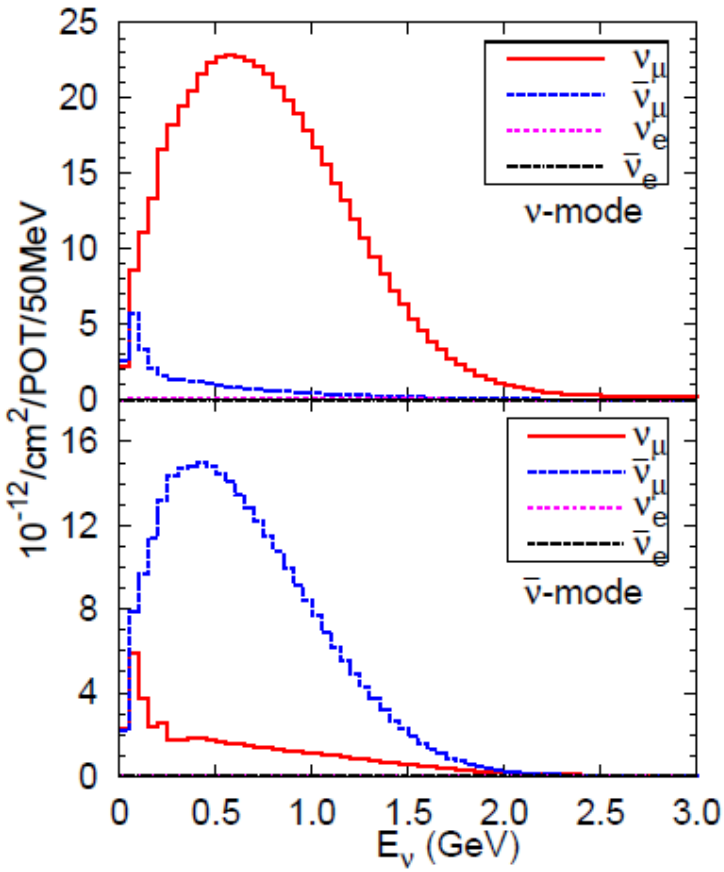


NCγ events at MiniBooNE

- 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)



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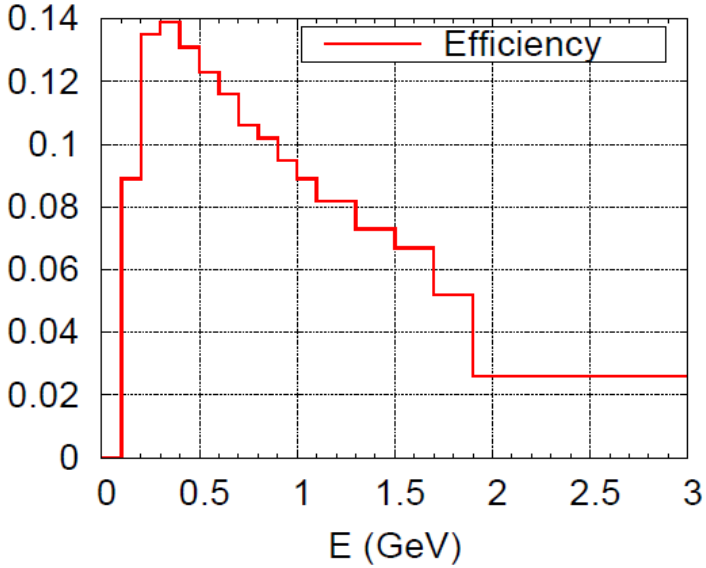

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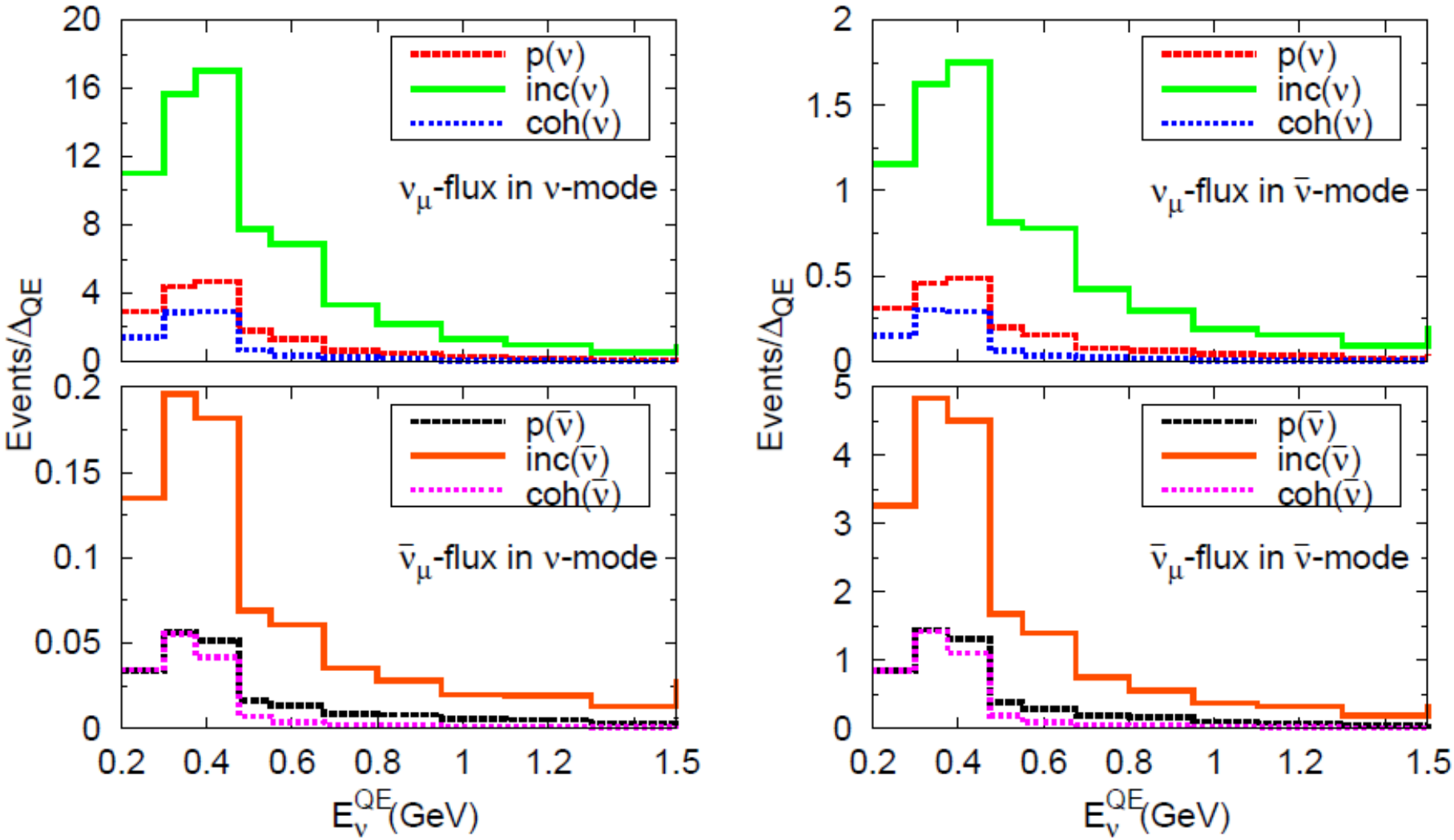

- 30-40 % of ν induced events in $\bar{\nu}$ mode

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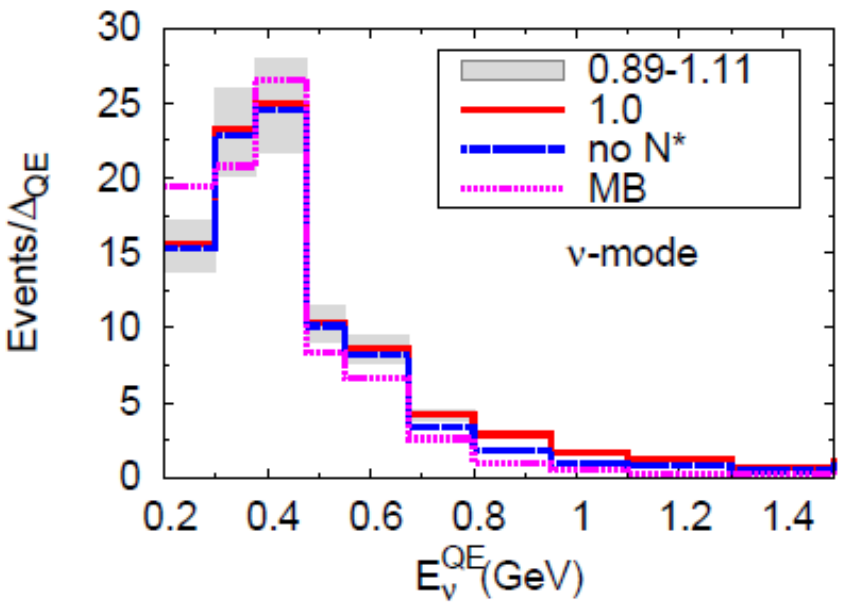
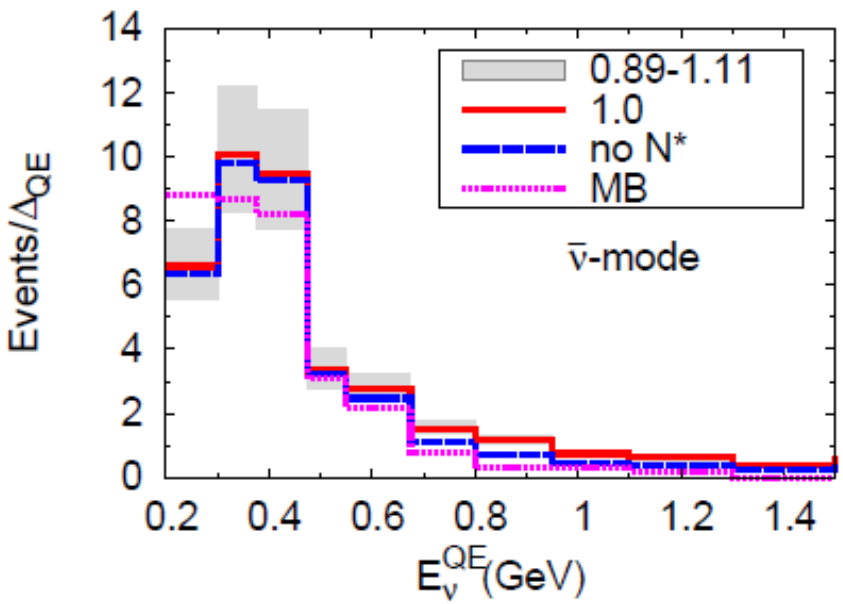
- Comparison to the MiniBooNE estimate





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

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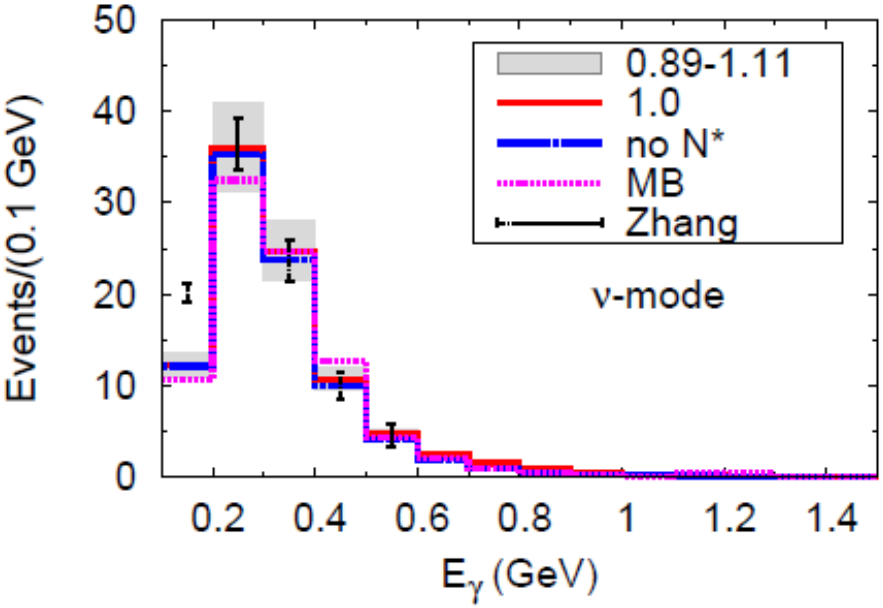
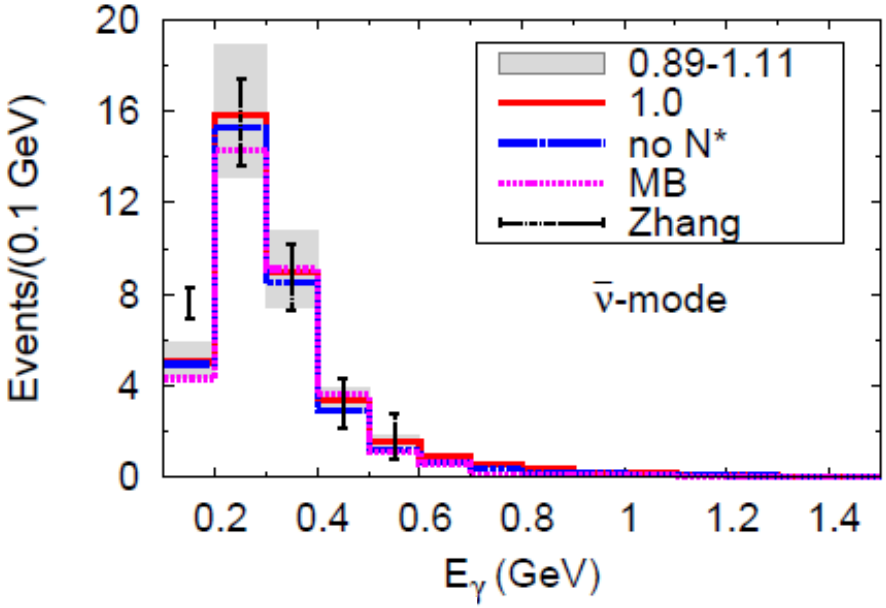
- Comparison to the MiniBooNE estimate and to Zhang, Serot, PLB 719 (2013)





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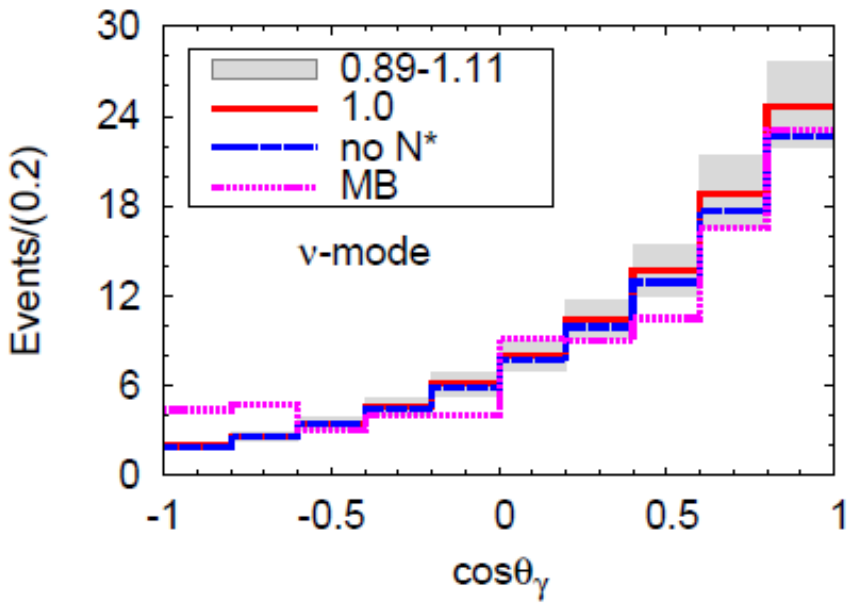

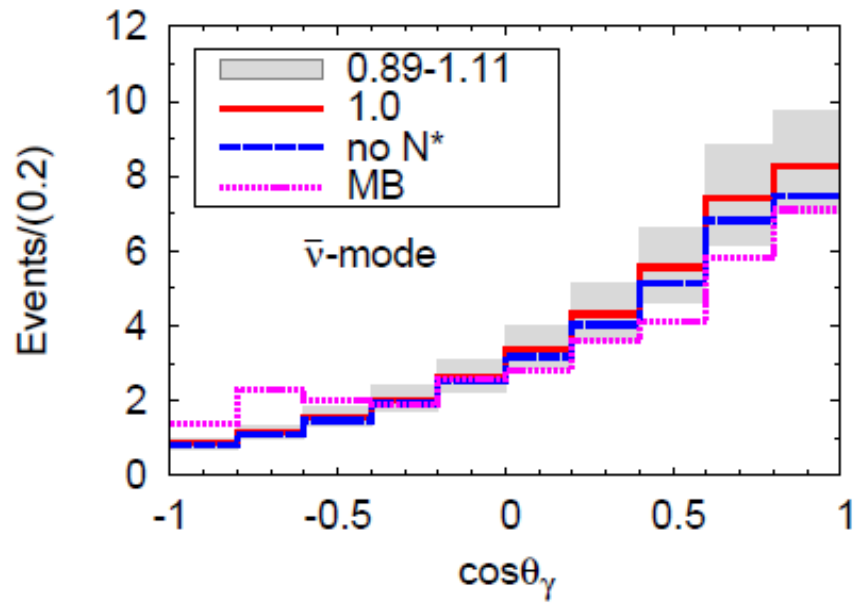

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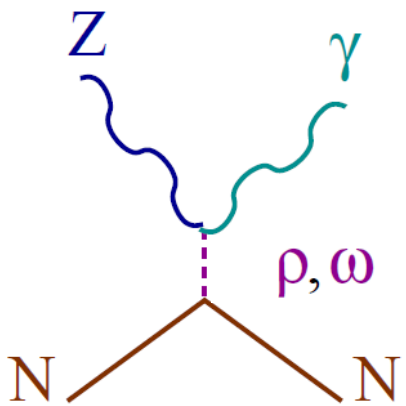
- Comparison to the MiniBooNE estimate
  - NCγ : insufficient to explain the excess of e-like events at MiniBooNE
  - Same conclusion as Zhang, Serot, PLB 719 (2013)

NCγ events at MiniBooNE

- Origin of e-like event excess @ MiniBooNE
  - Unaccounted backgrounds?

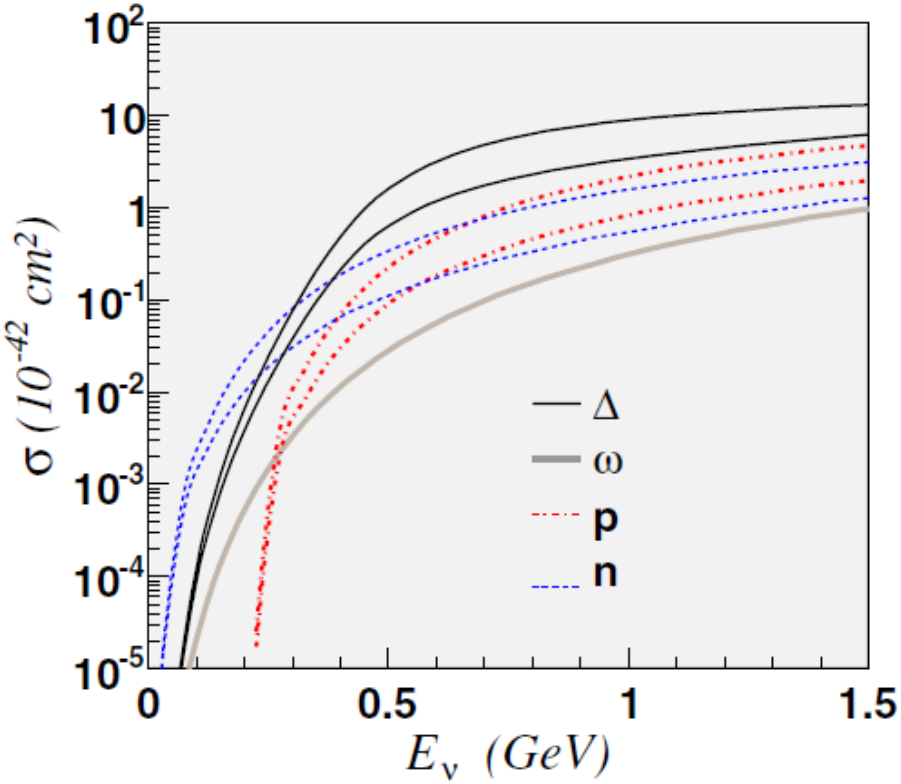


- Harvey et al., PRL 99 (2007)
- ω favored: large (uncertain) isoscalar ωNN coupling

The model

- R. Hill, PRD 81 (2010)

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



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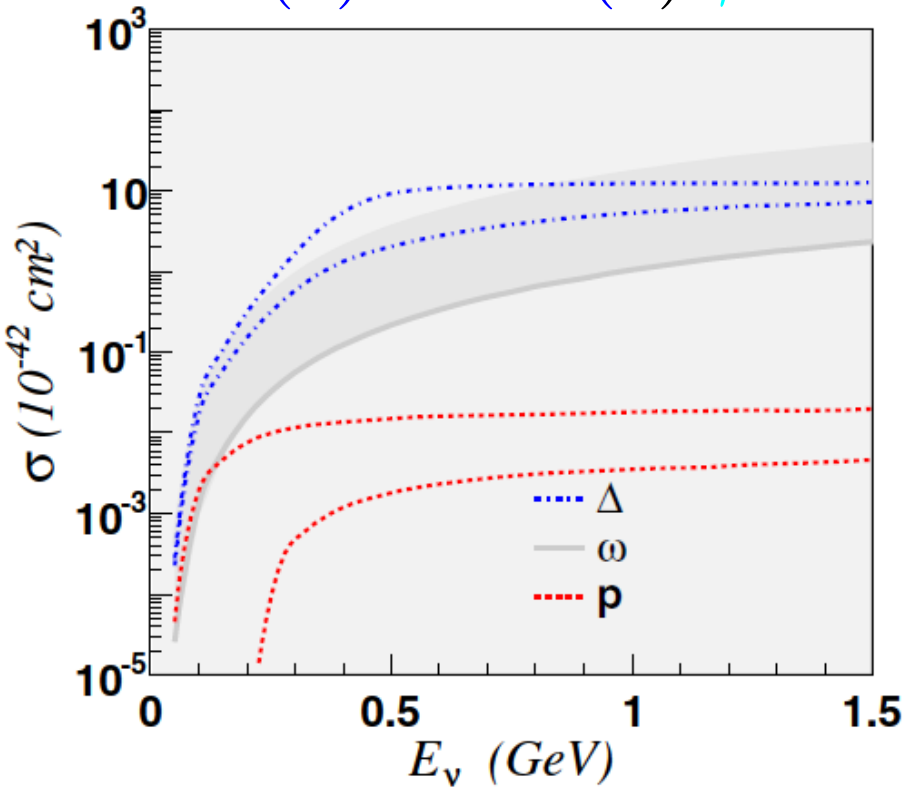
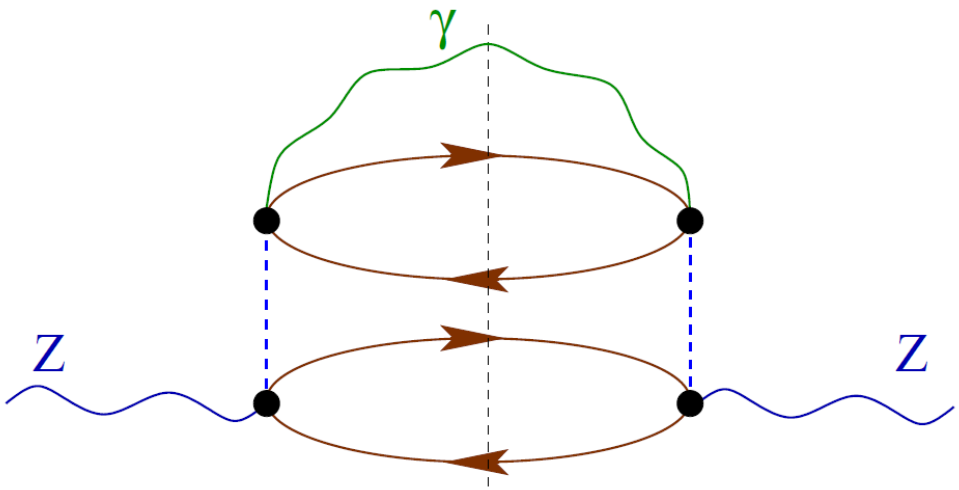


- The ω exchage contribution is very small
- J. Rosner, PRD 91 (2015) ⇒ ¼ smaller
  - Z-ω-γ vertex calibrated by $\tau \rightarrow \nu_\tau\, a_1$ and $f_1 \rightarrow \rho\, \gamma$ decays

NCγ events at MiniBooNE

- Origin of e-like event excess @ MiniBooNE
  - Unaccounted backgrounds? No
  - Multi-nucleon contributions
    - $Z\ NN \to NN\ \pi$, $Z\ NN \to NN\ \gamma$



    - LAR, J. Nieves, E. Wang, work in progress
    - 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)
  - Lorentz violation T. Katori et al., PRD 74 (2006)
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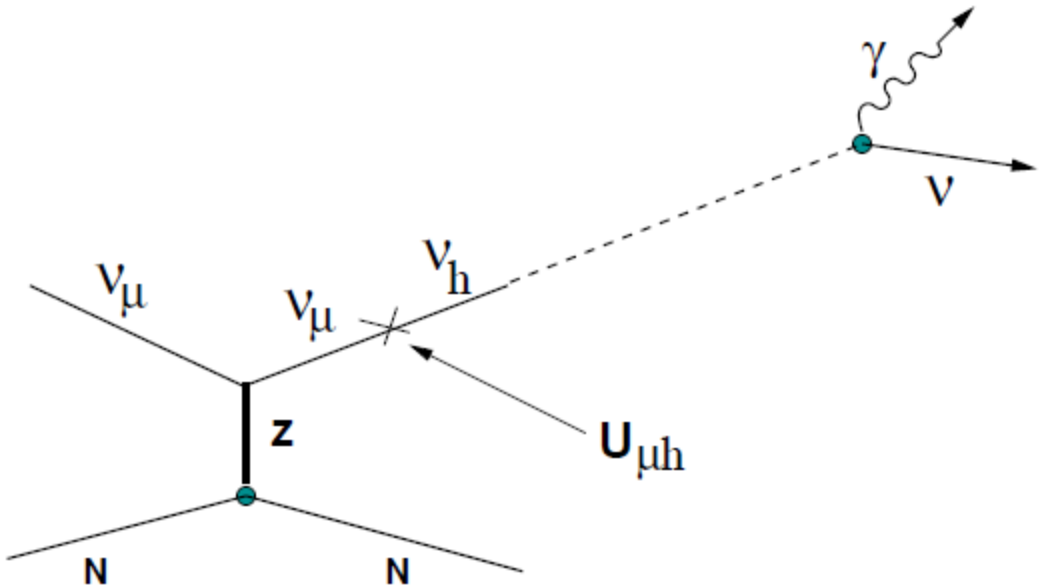
    - $m_h \approx 50$ MeV, $|U_{\mu h}|^2 \approx 10^{-3}$- 10^{-2}, $\tau_h < 10^{-9}$ s



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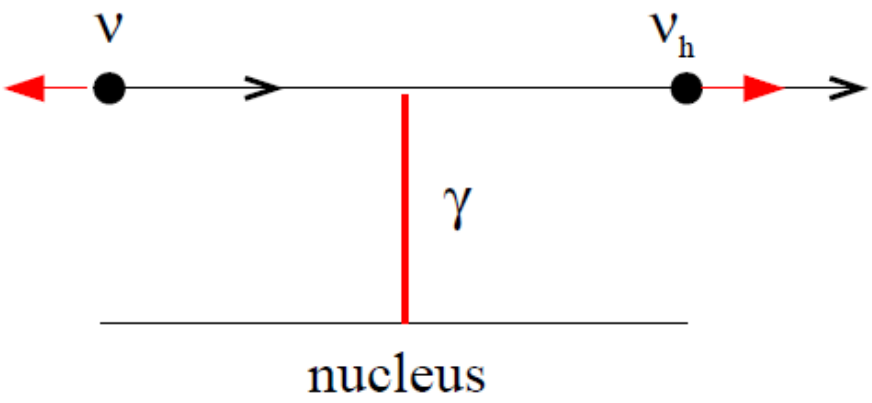

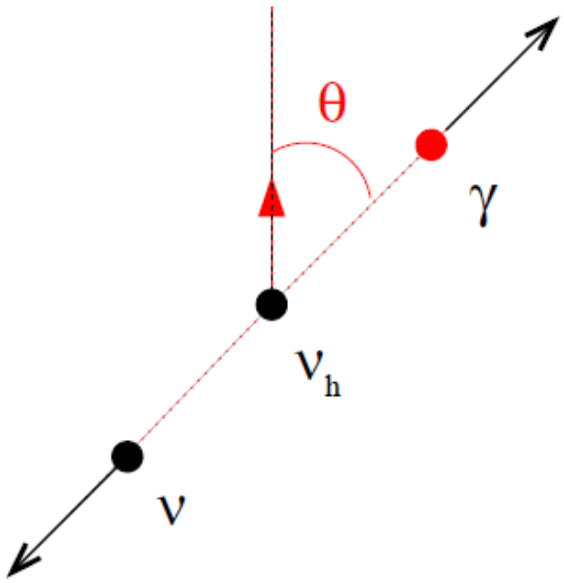

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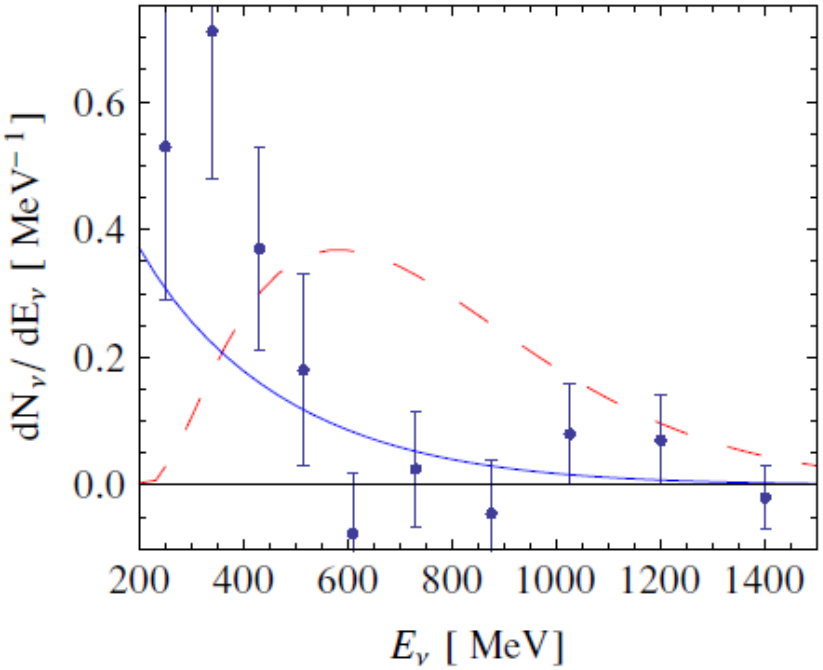
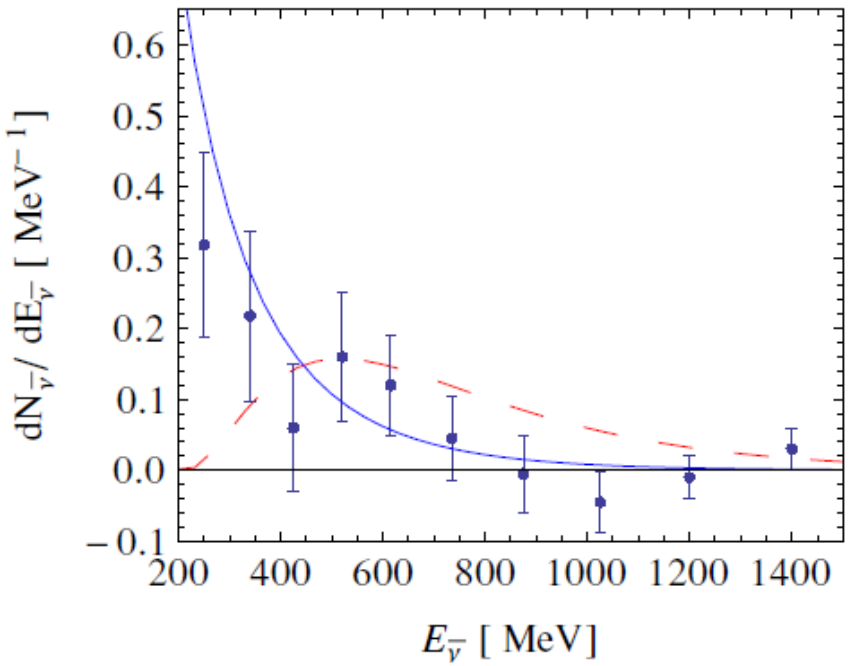




NCγ events at NOMAD

- Kullenberg et al., PLB 706 (2012)

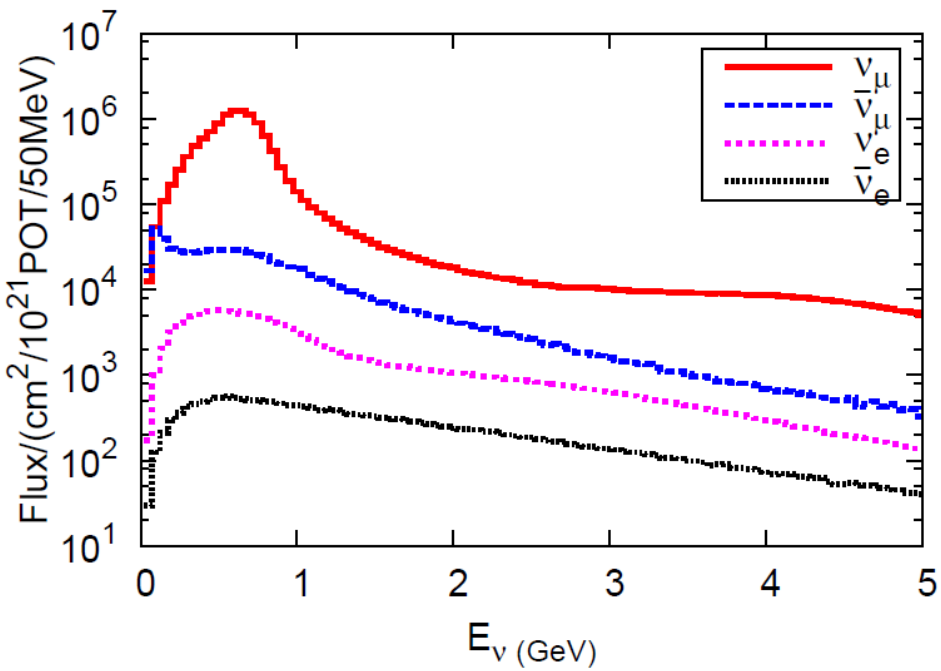
$$\frac{\sigma(\mathrm{NC}\gamma)}{\sigma(\nu_\mu A \to \mu^- X)} < 4.0 \times 10^{-4}$$ at 90 % CL

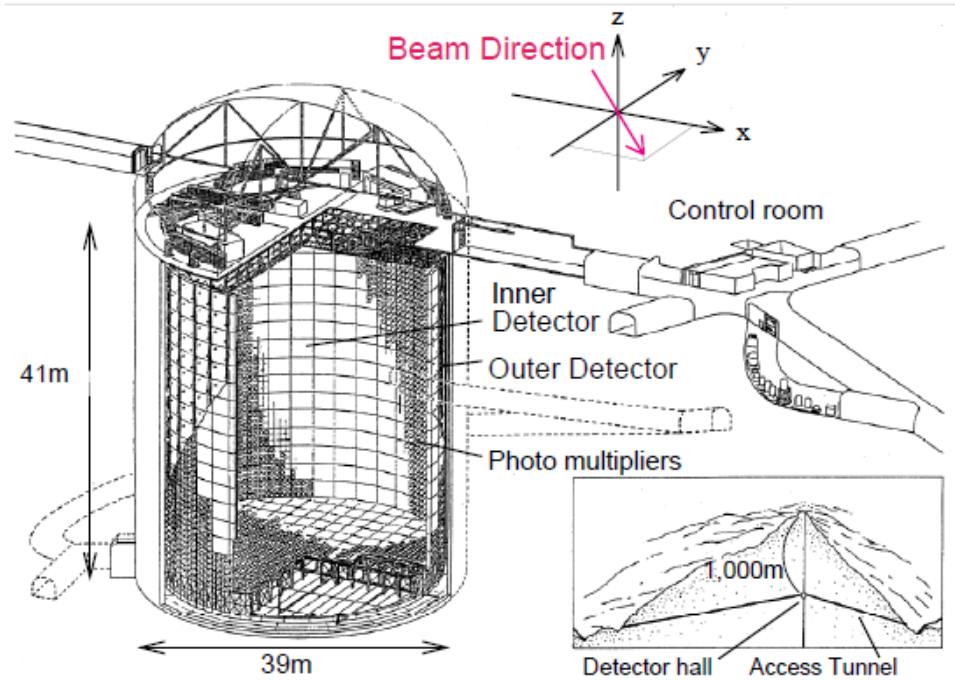
- Constraint to models attempting to explain the MiniBooNE anomaly (γ)
- In our case:
  - W γ_N < 1.6 GeV
  - Up to the extent that high q^2 extrapolations of the FF can be trusted
  - Neglecting nuclear effects

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

NCγ events at T2K

- Target: H_2O Abe et al, PRL 112 (2014) 061802
- Mass: 22.5 ktons
- POT: 6.57 x 10^{20} (ν mode)
- Fluxes: SK250 100 MeV < E_ν < 3 GeV Abe et al, PRD 87 (2013)





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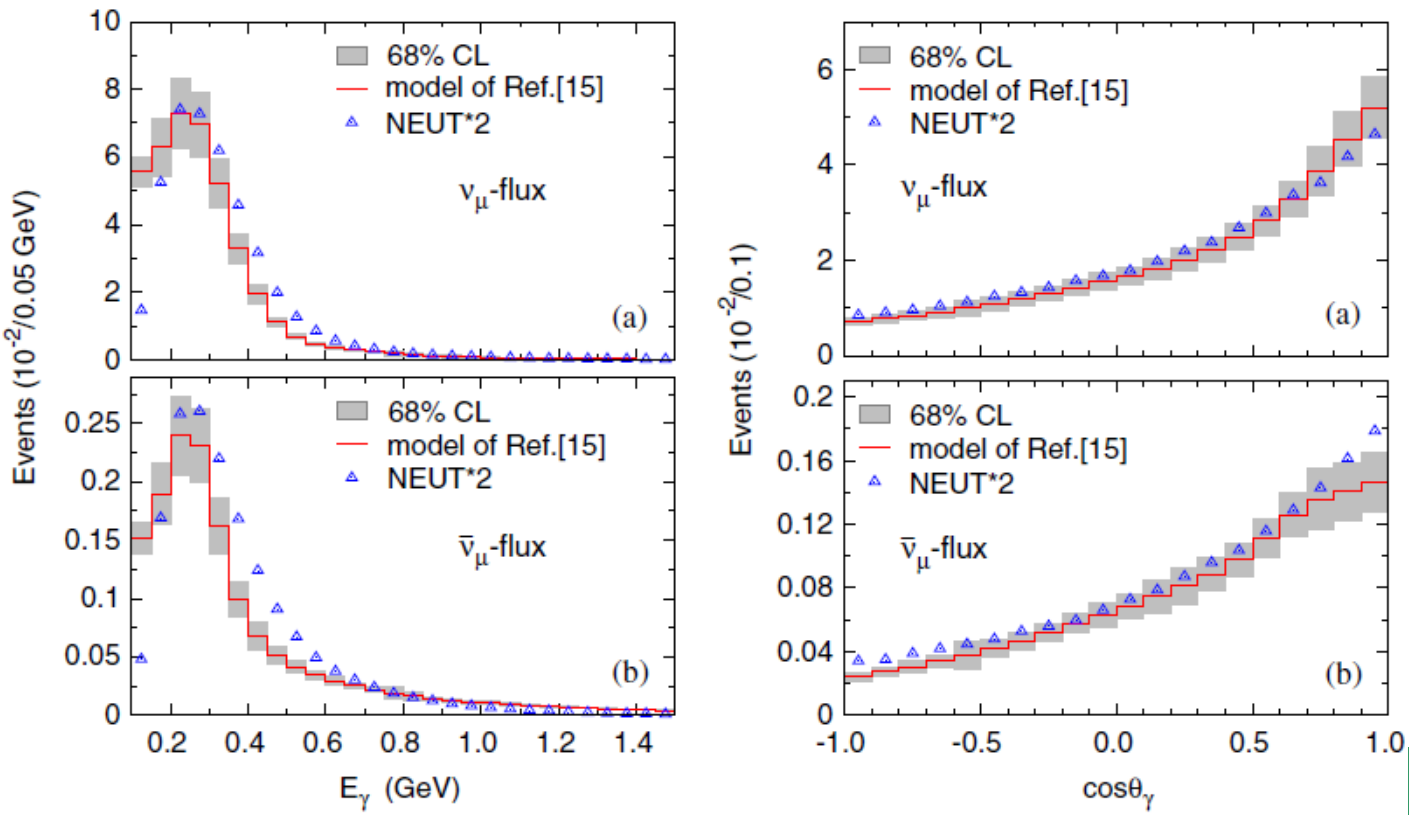

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$$N_{tot} = 0.427 \pm 0.050 \quad \text{vs} \quad N_{NEUT} = 0.217$$

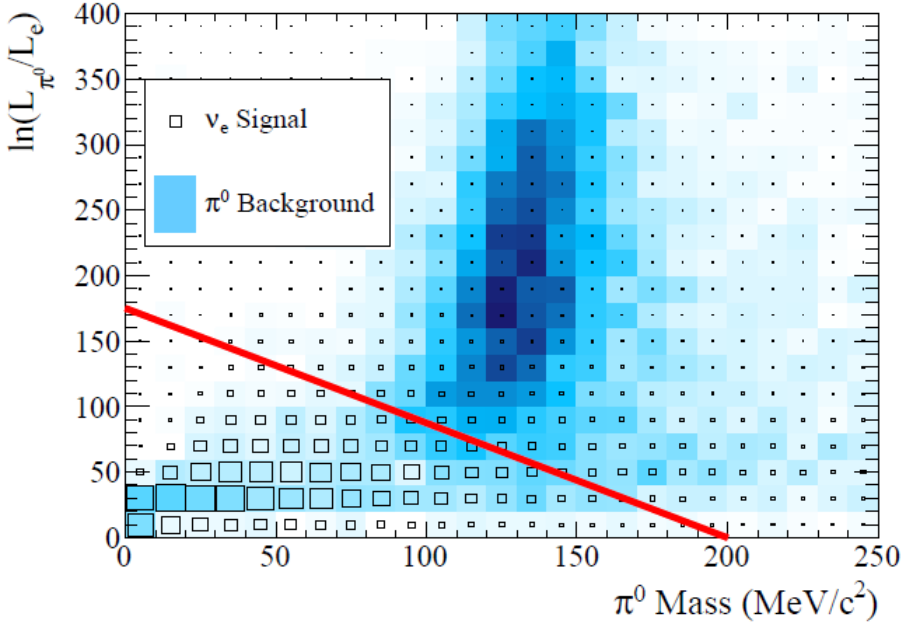
- Does this discrepancy matter?
  - For θ_{13}?: probably not.

NCγ events at T2K

- Target: H_2O
- Mass: 22.5 ktor
- POT: 6.57 x 10
- Fluxes: SK250 :
- Comparison to

N_{tot} = 0.427 :

Abe et al, PRL 112 (2014) 061802



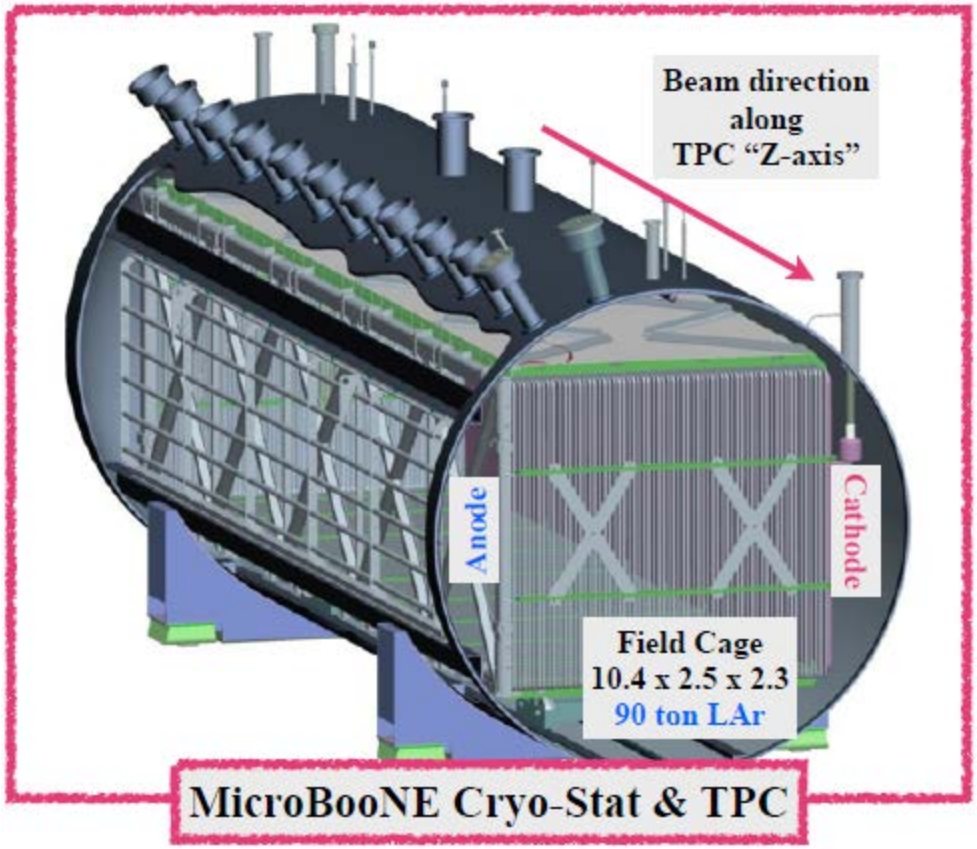
37 (2013)

, PRD92 (2015)

- Does this discrepancy matter?
  - For θ_{13}?: probably not.
  - Better π^o rejection cut ⇒ NCγ relatively more important
  - For CP violation searches? perhaps...

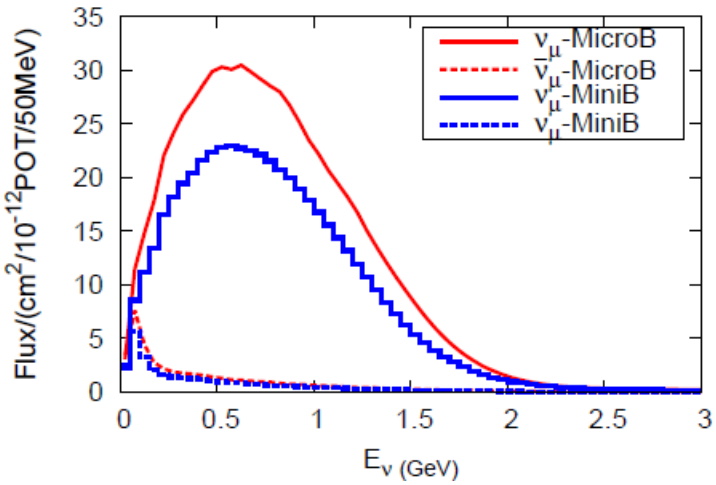
MicroBooNE

- 170 ton LArTPC
- Located along the Booster neutrino beam line
- Distinguishes electrons from photons



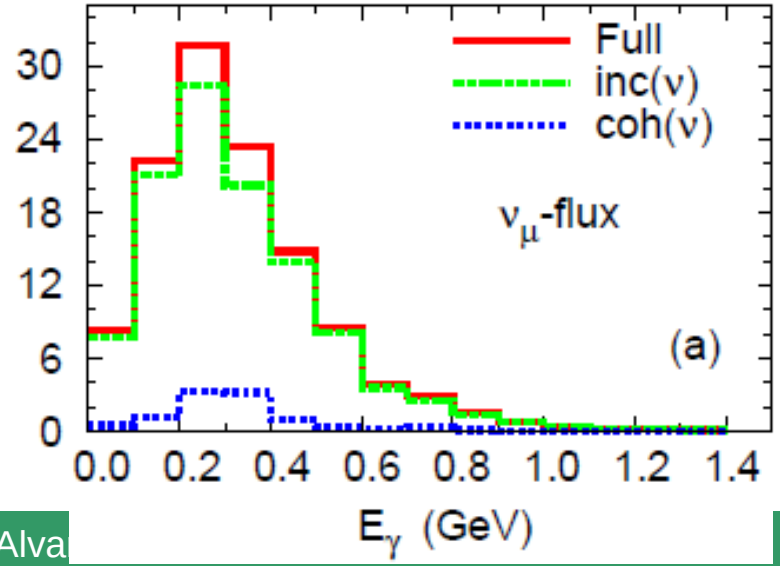
MicroBooNE

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

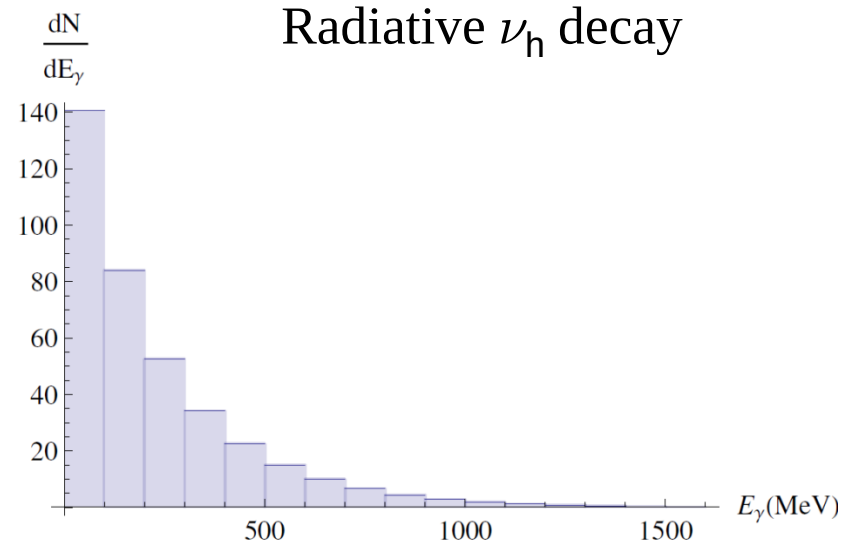


- LAR, E. Saul, E. Wang, preliminary

Standard

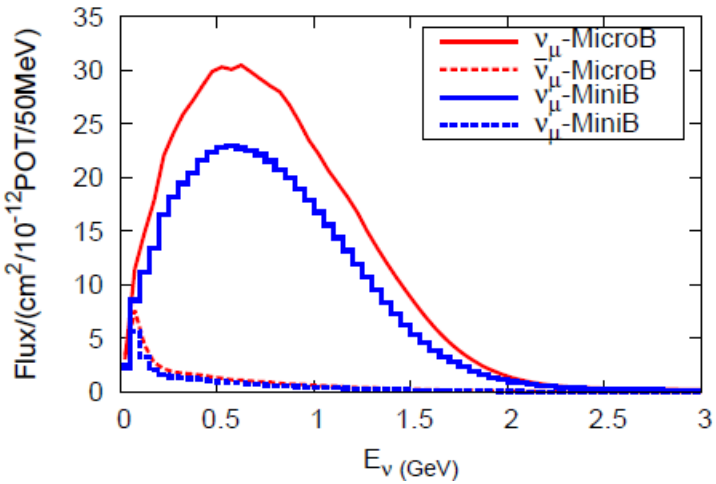


Radiative ν_h decay



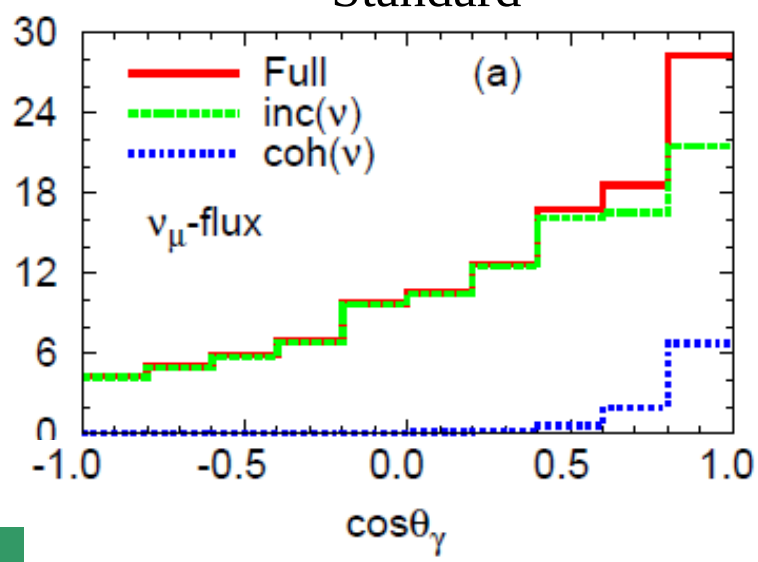
MicroBooNE

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

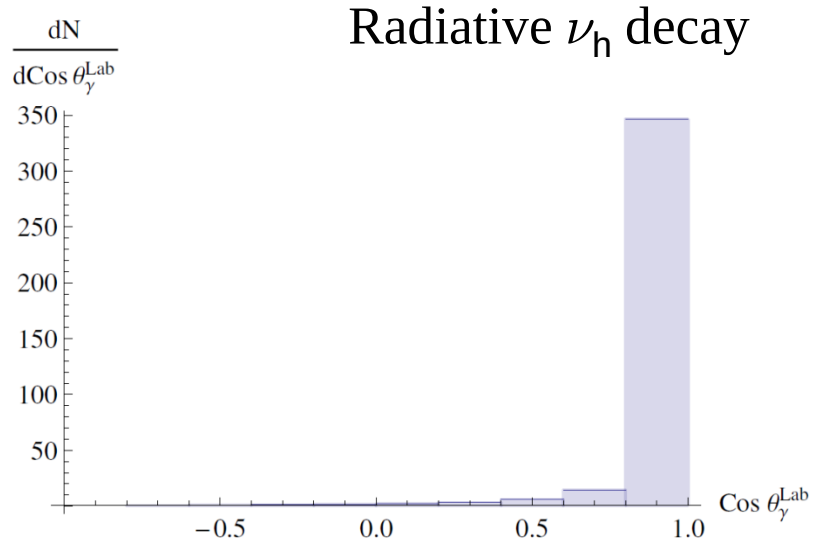


- LAR, E. Saul, E. Wang, preliminary

Standard



Radiative ν_h decay



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).
- NCγ : insufficient to explain the excess of e-like events at MiniBooNE
- NOMAD limit respected
- Implications for T2K discussed: twice more NCγ events predicted vs NEUT
- Predictions for MicroBooNE with both standard mechanism and radiative decay of heavy ν
- Details in: E. Wang, LAR, J. Nieves, PRC 89 (2014) 015503; PLB 740 (2015) 16;
  E. Wang, LAR, Y. Hayato, K. Mahn, J. Nieves, PRD92 (2015) 053005