Photon emission in (anti)neutrino neutral current interactions

En Wang, Luis Alvarez-Ruso and Juan Nieves

IFIC, Universidad de Valencia, Spain

NuFact 2013, Beijing

Overview

Introduction

Introduction

neutrino (antineutrino)

ν_e, ν_μ, ν_τ ($\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$)

neutrino oscillations

caused by nonzero neutrino masses and neutrino mixing.

neutrino experiments

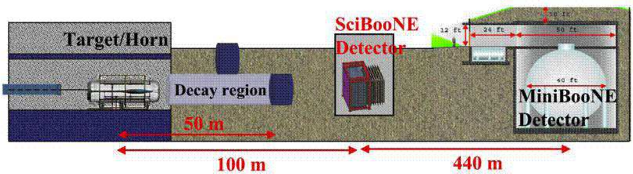
T2K, MINOS, Daya Bay, RENO, Double Chooz
LSND,MiniBooNE ...

neutrino cross section

crucial to understand the detection process and systematic uncertainties.
nuclear targets: ^{12}C, ^{16}O, Fe, A_r,...

MiniBooNE experiment

$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations



- CCQE: $\nu N \to eN'$
- CCπ: $\nu N \to eN'\pi$
- NCπ: $\nu N \to \nu N\pi$
- NCγ: $\nu N \to \nu N\gamma$
- others

Cherenkov detector: 806 tons of pure mineral oil ($^{12}CH_2$)

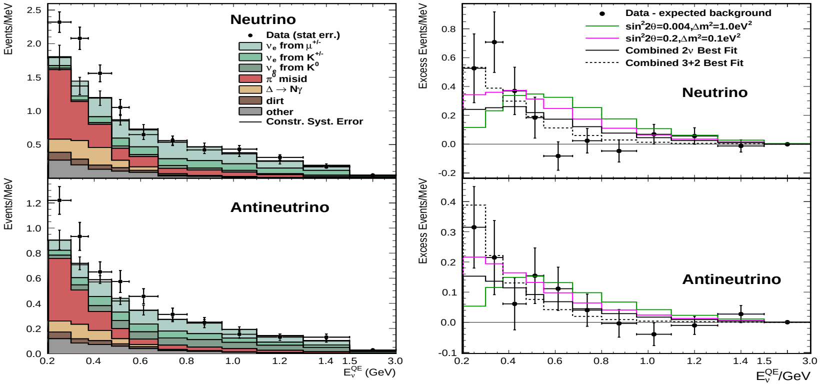
Background of the MiniBooNE experiment

Because the MiniBooNE detector cannot distinguish the signature produced by electrons or photons, the ν_e and $\bar{\nu}_e$ CCQE background events include

- NC π^0 where the $\gamma\gamma$ decay is not identified
- NCγ decay - the second largest
- others

(arXiv:1207.4809 [hep-ex])

e-like events in the MiniBooNE experiment



- neutrino-mode excess: 162.0 ± 47.8 events
- antineutrino-mode excess: 78.4 ± 28.5 events

Previous theoretical models

R.J.Hill (Phys.Rev.D84,013008 and D84,017501)

- a microscopic model: nucleons, $\Delta(1232)$ resonance and mesons.
- treat the target as an ensemble of nucleons, neglecting nuclear-medium corrections
- claims that NCγ can explain the excess of e-like events

X.Zhang, B.D.Serot(Phys.Lett.B719,409-414)

- based on the chiral effective field theory in a nuclear medium
- the result is close to the MiniBooNE estimate

Theoretical model

Amplitude for NCγ on the nucleon

The reaction is,

$$\nu(k) + N(p) \rightarrow \nu(k') + N(p') + \gamma(q_\gamma)$$

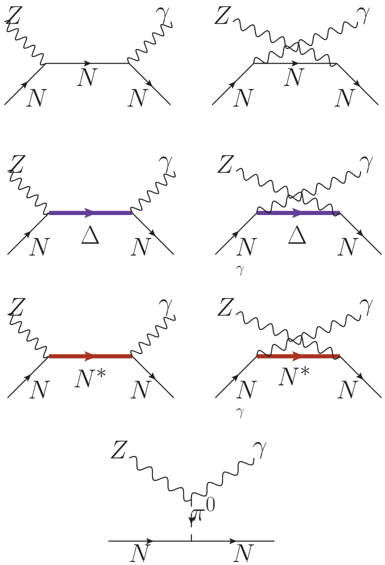
The amplitude is given by,

$$\begin{aligned} \mathcal{M}_r &= \frac{G_F e}{\sqrt{2}} l_\alpha \mathcal{J}_r^\alpha \\ &= \frac{G_F e}{\sqrt{2}} \bar{u}_\nu(k')\gamma_\alpha(1 \mp \gamma_5)u_\nu(k) \times \left(i\epsilon_\mu^{*(r)} \bar{u}(p')\Gamma^{\mu\alpha} u(p) \right), \end{aligned}$$

- the $\mp$ is for neutrino and antineutrino, respectively.
- ϵ_μ is the photon polarization vector.
- $\Gamma^{\mu\alpha}$ is the hadronic matrix element.

(arXiv:1304.2702 [nucl-th])

Model for the hadronic matrix elements



- First row: direct and crossed nucleon pole terms
- Second row: direct and crossed $\Delta(1232)$ pole terms
- Third row: direct and crossed heavier resonance ($N(1440)$, $N(1520)$ and $N(1535)$) pole terms
- Forth row: $t-$channel pion exchange term

Nucleon pole terms

$$\Gamma_N^{\mu\alpha} = \tilde{J}^{\mu}_{EM}(q_\gamma)(\not{p} + \not{q} + M) J^{\alpha}_{NC}(q) D_N(p+q)$$
$$+\tilde{J}^{\alpha}_{NC}(-q)(\not{p}' - \not{q} + M) J^{\mu}_{EM}(-q_\gamma) D_N(p'-q)$$

where $\tilde{J} = \gamma_0 J^\dagger \gamma_0$, and D_N is the nucleon propagator, given by,

$$D_N(p) = \frac{1}{\not{p} - M}.$$

The weak NC and electromagnetic (EM) currents are given by,

$$J^{\alpha}_{NC}(q) = \gamma^\alpha \tilde{F}_1(q^2) + \frac{i}{2M}\sigma^{\alpha\beta} q_\beta \tilde{F}_2(q^2) - \gamma^\alpha \gamma_5 \tilde{F}_A(q^2),$$
$$J^{\mu}_{EM}(q_\gamma) = \gamma^\mu F_1(0) + \frac{i}{2M}\sigma^{\mu\nu} q_{\gamma\nu} F_2(0),$$

$\Delta(1232)$ pole terms

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

where the propagator D_Δ is,

$$D_\Delta(p) = \frac{1}{p^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta(p^2)},$$

$\Lambda^{\mu\nu}$ is the spin 3/2 projection operator, which is given by in the momentum space,

$$\Lambda^{\mu\nu}(p_\Delta) = -(\not{p}_\Delta + M_\Delta)\left[g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{2}{3}\frac{p_\Delta^\mu p_\Delta^\nu}{M_\Delta^2} + \frac{1}{3}\frac{p_\Delta^\mu\gamma^\nu - p_\Delta^\nu\gamma^\mu}{M_\Delta}\right].$$

Γ_Δ is the resonance width.

$\Delta(1232)$ pole terms

The weak NC and EM currents are given by,

$$J^{\beta\mu}_{NC}(p,q) = \left[\frac{\tilde{C}^V_3}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{\tilde{C}^V_4}{M^2}(g^{\beta\mu} q\cdot p_\Delta - q^\beta p^\mu_\Delta) + \frac{\tilde{C}^V_5}{M^2}(g^{\beta\mu} q\cdot p - q^\beta p^\mu)\right]\gamma_5 + \frac{\tilde{C}^A_3}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{\tilde{C}^A_4}{M^2}(g^{\beta\mu} q\cdot p_\Delta - q^\beta p^\mu_\Delta) + \frac{\tilde{C}^A_5}{M^2} g^{\beta\mu} + \frac{\tilde{C}^A_6}{M^2} q^\beta q^\mu,$$

$$J^{\beta\mu}_{EM}(p,-q_\gamma) = -\left[\frac{C^V_3}{M}(g^{\beta\mu}\not{q}_\gamma - q'^\beta_\gamma\gamma^\mu) + \frac{C^V_4}{M^2}(g^{\beta\mu} q_\gamma\cdot p_{\Delta c} - q^\beta_\gamma p^\mu_{\Delta c}) + \frac{C^V_5}{M^2}(g^{\beta\mu} q_\gamma\cdot p - q^\beta_\gamma p^\mu)\right]\gamma_5,$$

$p_\Delta = p + q = p' + q_\gamma$ and $p_{\Delta c} = p' - q = p - q_\gamma$.

$\Delta(1232)$ axial form factors

In this work, we assume a standard dipole form for the axial NC form factors

$$\begin{aligned}
\tilde{C}_5^A(Q^2) &= -C_5^A(0)\left(1+\frac{Q^2}{M_A^2}\right)^{-2}, \\
\tilde{C}_6^A(Q^2) &= \frac{M^2}{m_\pi^2+Q^2}\tilde{C}_5^A(Q^2), \\
\tilde{C}_4^A(Q^2) &= -\frac{\tilde{C}_5^A(Q^2)}{4}, \\
\tilde{C}_3^A(Q^2) &= 0,
\end{aligned}$$

The cross section depends strongly on $\tilde{C}_5^A$. We take $C_5^A(0) = 1.0 \pm 0.11$ (Phys. Rev. D **81**, 085046 (2010)).

$\Delta(1232)$ vector form factors

The vector EM form factor can be derived from helicity amplitudes extracted from electron scattering experiments.
The relations between the vector form factors and the helicity amplitudes are complicated. (T.Leitner PhD thesis 2009)

π pole term

$$\Gamma^{\mu\alpha} = -iC_{p,n}\frac{g_A}{4\pi^2 f_\pi^2}\left(\frac{1}{2} - 2sin^2\theta_W\right)\epsilon^{\sigma\delta\mu\alpha}q_{\gamma\sigma}q_\delta(\not{p}'-\not{p})\gamma_5 D_\pi(p'-p),$$

$C_{p,n} = \pm 1$. The propagator is given by,

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

N^* pole term

The hadronic matrix elements of the N^* pole terms are constructed in the same way that we have done for the N ($N(1440)$, $N(1535)$) or $\Delta(1232)$ pole terms ($N(1520)$), For simplicity, We do not give details here.
We derive the vector form factors from the helicity amplitudes, and assume a standard dipole form for the axial form factors.

NCγ on nuclei

It consists of the incoherent and coherent reactions.

$$\nu(k) + A(p) \to \nu(k') + X(p') + \gamma(q_\gamma)$$

For the incoherent reaction, the final nucleus is either broken or left in some excited state.

$$\nu(k) + A_Z|_{gs}(p_A) \to \nu(k') + A_Z|_{gs}(p'_A) + \gamma(q_\gamma)$$

For the coherent reaction, the final nucleus is left in its ground state.

Nuclear effects

Fermi motion

We adopt the relativistic local Fermi gas approximation. The target nucleon moves in a local Fermi sea of momentum k_F defined as a function of the local density of protons and neutrons, independently.

Pauli blocking

Final nucleons are not allowed to take occupied states.

In-medium modification of Δ properties

The Δ resonance acquires a selfenergy because of several effects such as Pauli blocking of the final nucleon and absorption processes: $\Delta N \to NN$, $\Delta N \to NN\pi$ or $\Delta NN \to NNN$.

Incoherent reaction

The differential cross section for the incoherent reaction is,

$$d\sigma^A = 2 \int d^3\vec{r} \int \frac{d^3\vec{p}}{(2\pi)^3} n_N(\vec{p},\vec{r}) \left[1 - n_N(\vec{p}\,',\vec{r})\right] d\sigma^N,$$

where $k_F(\vec{r})$ is the Fermi momentum, given by,

$$k_F(\vec{r}) = \left[3\pi^2\rho(\vec{r})\right]^{1/3},$$

In-medium corrections are taken into account by making the substitutions, $\Gamma_\Delta/2 \to \Gamma_{\rm Pauli}/2 - {\rm Im}\Sigma_\Delta$ in the Δ propagator, where Σ_Δ is the selfenergy of $\Delta(1232)$.

Coherent reaction

The amplitude is given by,

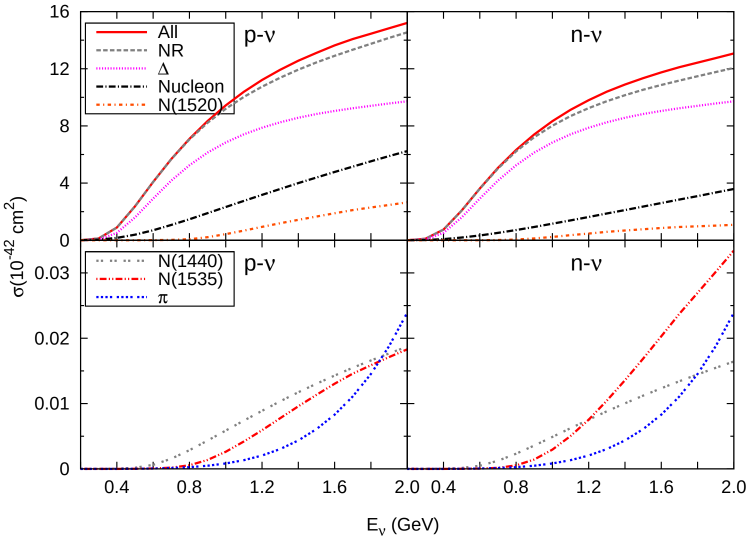
$$\mathcal{M}_r = \frac{G_F}{\sqrt{2}} l_\alpha J^\alpha_{coh(r)},$$

the hadronic current $J^\alpha_{coh(r)}$ is given by,

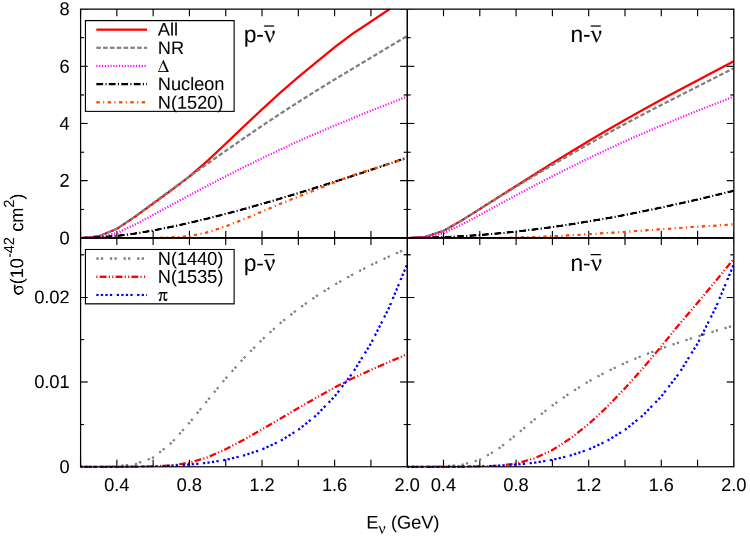
$$\begin{aligned} J^\alpha_{coh(r)} &= ie\epsilon^{*(r)}_\mu \int d^3\vec{r}\; e^{\mathrm{i}(\vec{q}-\vec{q}_\gamma)\cdot\vec{r}} \frac{1}{2} \mathrm{Tr}\left[\bar{u}(p')(\rho_p \Gamma^{\mu\alpha}_p + \rho_n \Gamma^{\mu\alpha}_n) u(p)\right] \\ &= ie\epsilon^{*(r)}_\mu R^{\mu\alpha}, \end{aligned}$$

Results

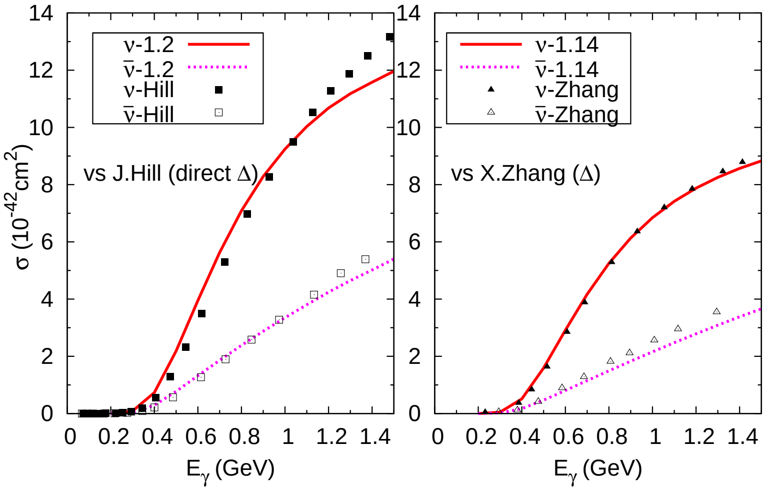
NCγ cross section on the nucleon for neutrino



The cross section of NCγ on nucleon for antineutrino

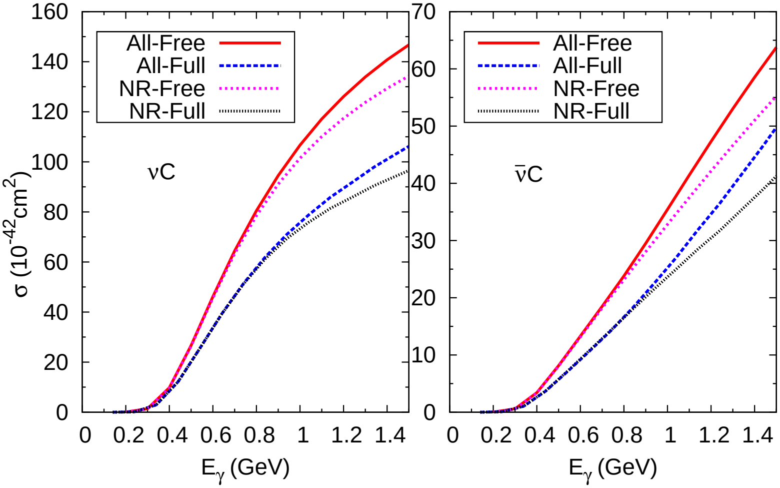


Comparison



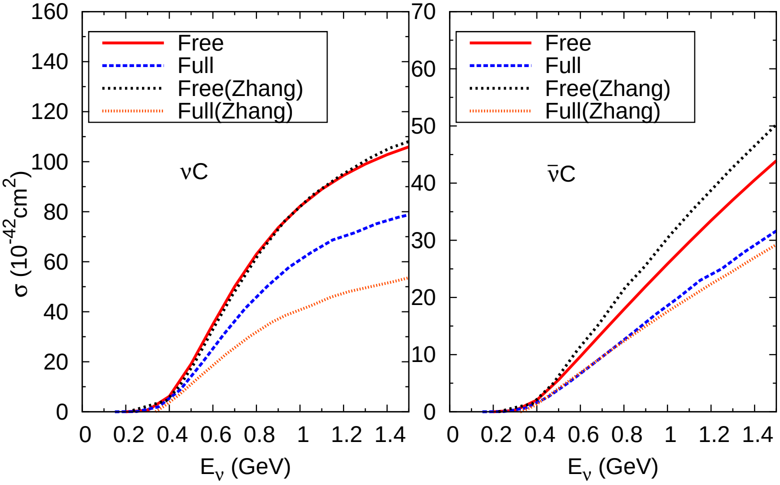
ν-1.2
ν̄-1.2
ν-Hill
ν̄-Hill
vs J.Hill (direct Δ)
σ (10^-42 cm^2)
E_γ (GeV)
ν-1.14
ν̄-1.14
ν-Zhang
ν̄-Zhang
vs X.Zhang (Δ)
E_γ (GeV)

Incoherent reaction



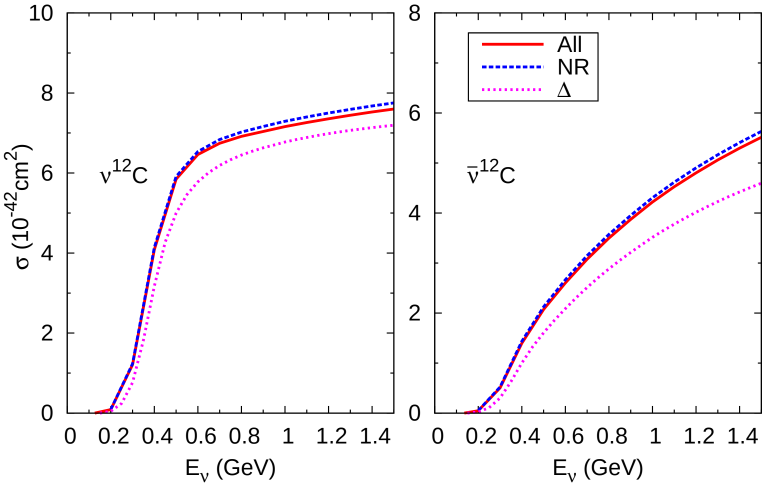
Nuclear effects reduce the cross section about 30%.

Incoherent reaction (Δ)

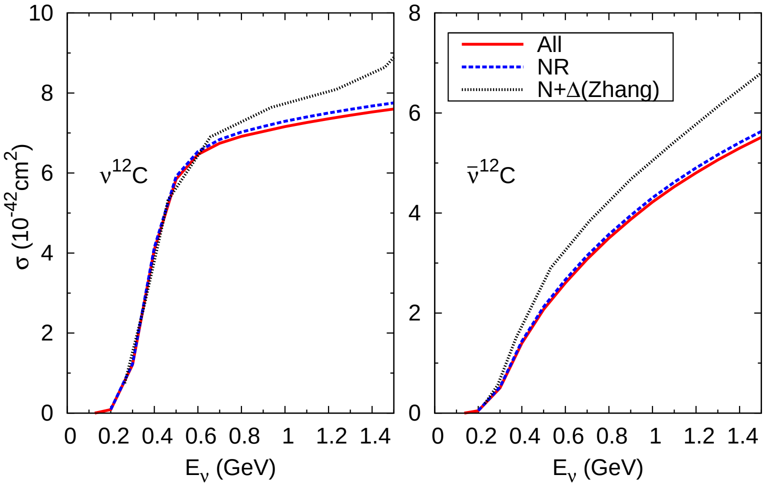


Nuclear effects reduce the cross section about 30%.

Coherent reaction



Coherent reaction



Comparison with the MB estimate

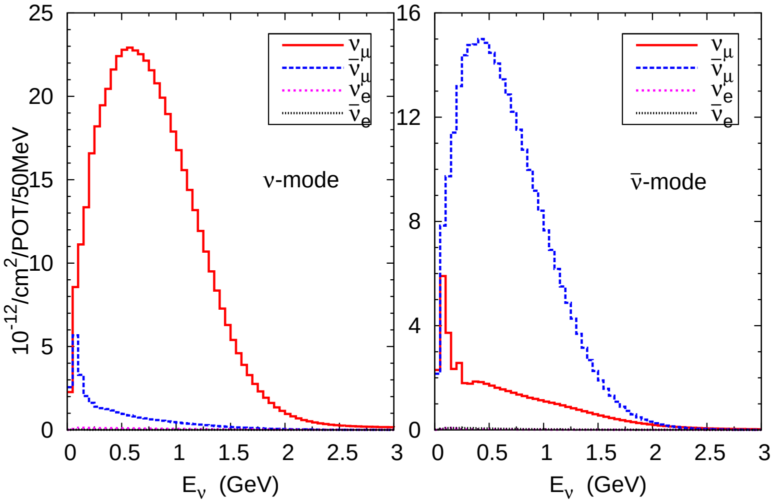
CCQE reconstructed (anti)neutrino energy

Assuming that the visible energy (E_e) is generated by an electron from $\nu_e + n \rightarrow p + e^-$, the reconstructed (anti)neutrino energy is given by,

$$E_\nu^{QE} = \frac{2(M_N - E_B)E_e - \left[E_B^2 - 2M_N E_B + m_e^2 + \Delta M^2\right]}{2\left[(M_N - E_B) - E_e(1 - cos\theta_e)\right]},$$

For a photon which is mis-identified as an electron in the MiniBooNE detector, we have to replace E_e and θ_e by E_γ and θ_γ. (Phys. Rev. D **84**, 072005 (2011))

Beam flux of the MiniBooNE



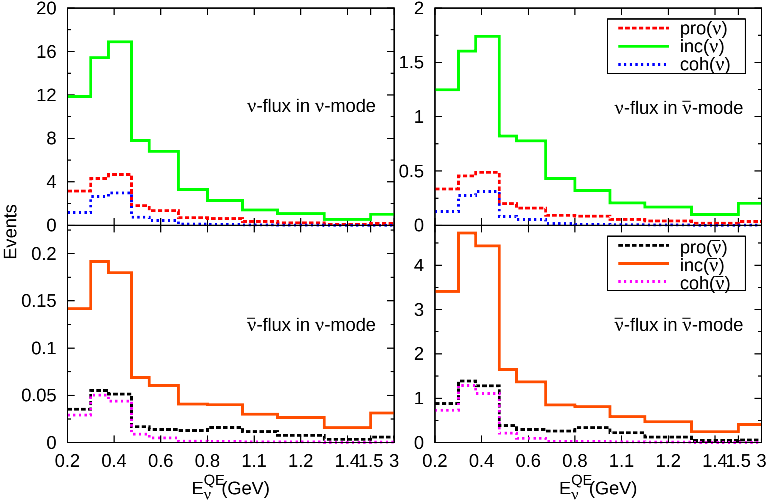
The events

NCγ events at the MiniBooNE detector is given by,

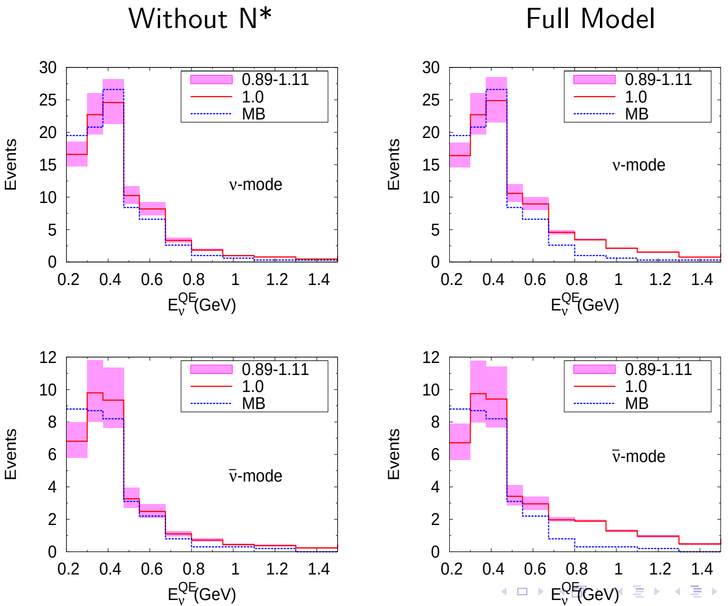
$$N = [\sigma_{\nu N \to \nu N \gamma} \times N_{\mathrm{p}} + (\sigma_{\mathrm{incoh}} + \sigma_{\mathrm{coh}}) \times N_{^{12}\mathrm{C}}] \times N_\nu \times \rho_{\mathrm{effi}}$$

- σ's: cross section for NCγ on proton, incoherent and coherent reaction on Carbon
- N_ν : the number of incoming neutrino (antineutrino)
- $N_{\mathrm{p},^{12}\mathrm{C}}$: the number of protons and carbon nuclei, respectively in the target
- ρ_{effi}: the efficiency for photon/electron detection

E_ν^{QE} distribution for NCγ on CH_2

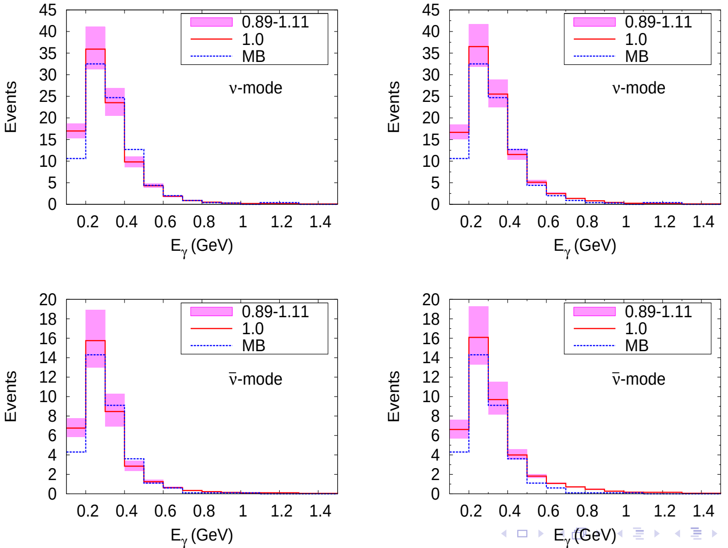


Comparison to the MB estimate



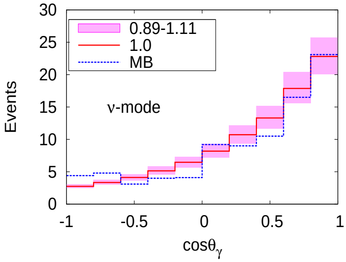
E_γ distribution of the photon events

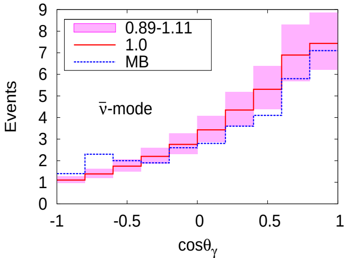
Without N* Full Model



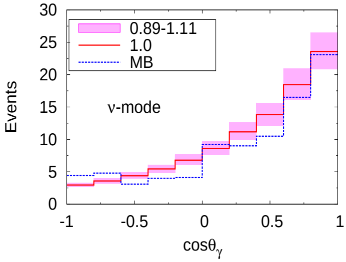
$cos\theta_\gamma$ distribution of the photon events

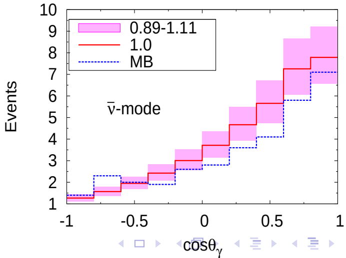
Without N*





Full Model





Summary

Summary

- We have studied NCγ on nucleons and nuclei in the energy region relevant for the MiniBooNE event excess.
- Our model consists of nucleon pole, Δ pole, heavier resonances pole and $t-$channel pion-exchange. For the heavier resonances, $N(1520)$ plays an important role in the NCγ.

Summary

- We extend the model to study the cross section off nuclei. Among others, we consider nuclear effects: Fermi motion, Pauli blocking, and in-medium modification of the Δ properties. Reduction: 30%.
- The cross sections of the coherent reaction is much smaller than those of incoherent reaction.

- Our predictions are consistent with the semi-empirical MiniBooNE estimate, and cannot explain the excess of e-like events.

Thanks for your attention!