Photon Emission in Neutral Current Interactions with Nucleons and Nuclei

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Overview

Introduction
A brief resume

Who am I?

- Name: En Wang
- Date of birth: Dec. 1985
- Marital status: Married
- The place of birth: Henan, China

Figure : Shao-Lin temple, Henan

Education

Ph.D — 03.2011 – 12.2014

IFIC, University of Valencia & CSIC, Valencia, Spain
Title: Electroweak processes in nucleons and nuclei at intermediate energies
Advisors: Drs. **Juan M. Nieves** and **Luis Alvarez-Ruso**

Master — 09.2007 – 07.2010

Department of Physics, Zhengzhou University, Henan, China
Title: Study of meson properties in quark models
Advisor: Prof. **De-Min Li**

Bachelor — 09.2003 – 07.2007

Department of Physics, Zhengzhou University, Henan, China
Title: Study of mass spectra of the charmonium
Advisor: Prof. **De-Min Li**

Research

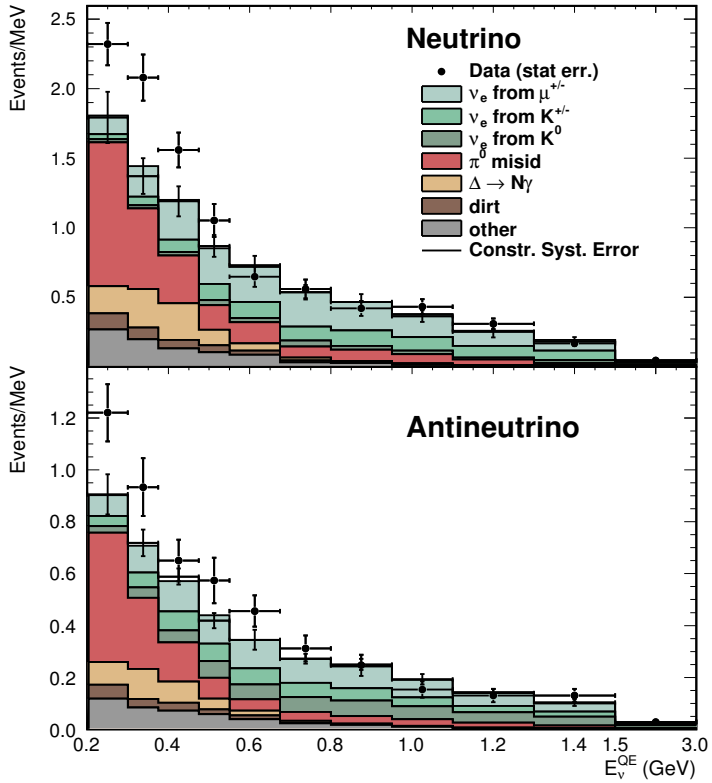
♣ Neutrino-nucleon and neutrino-nucleus interaction; Photon emission in neutral current interactions at intermediate energies

♣ Effective hadron interactions with chiral symmetry: Resonances and unitary re-summations

♣ Photo-production of the $\Lambda(1520)$ resonance

Introduction of NCγ theoretical study

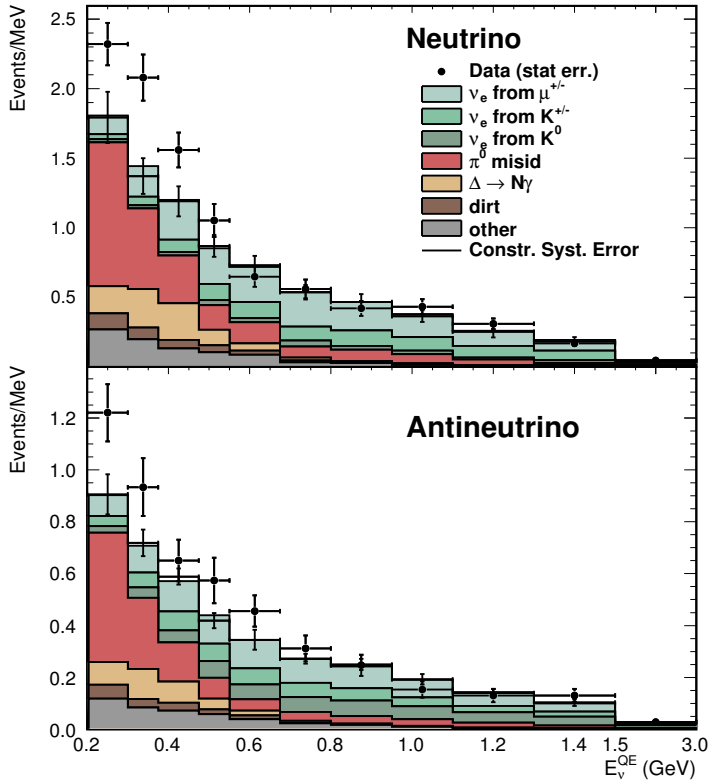
e-like events in the MiniBooNE experiment



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

A. Aguilar-Arevalo et al., PRL 110(2013),161801.

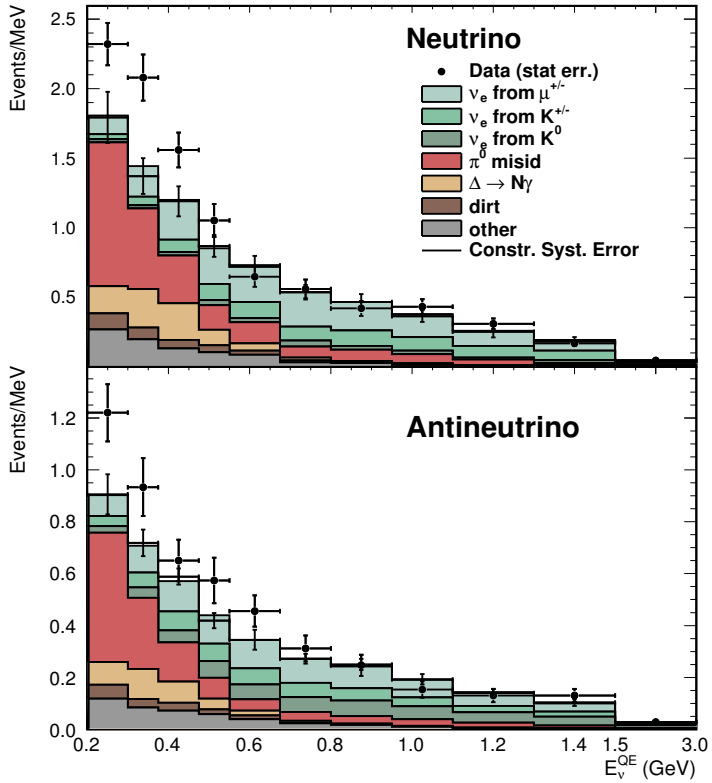
e-like events in the MiniBooNE experiment



This anomaly of e-like events

- Oscillation: not explained by 1, 2, 3 families of sterile neutrino. J. Conrad, et al., AHEP 2013(2013), 163897; C. Giunti, et al., PRD 88(2013), 073008.
- Lorentz violation. T. Katori PRD 74(2006), 105009.
- Radiative decay of heavy neutrinos. S. Gninenko, PRL 103(2009), 241802.

e-like events in the MiniBooNE experiment



It could have its origin in poorly understood background and unknown systematics.

- MiniBooNE detector cannot distinguish the signature produced by electrons or photons.
- NC π^0 where the $\gamma\gamma$ decay is not identified
- $\Delta \to N\gamma$ decay - one of the largest background

(A. Aguilar-Arevalo et al., PRL 110(2013), 161801)

Theoretical Model

NCγ on the nucleons and nuclei

- NCγ reaction on nucleons

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

- NCγ on nuclei consists of incoherent and coherent reactions,

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

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

At the relevant energies for MiniBooNE, the reaction is dominated by the excitation of the $\Delta(1232)$ resonance but there are also non-resonant contributions that, close to threshold, are fully determined by the effect ive chiral Lagrangian of strong interactions.

Amplitude for NCγ on the nucleon

The reaction is,

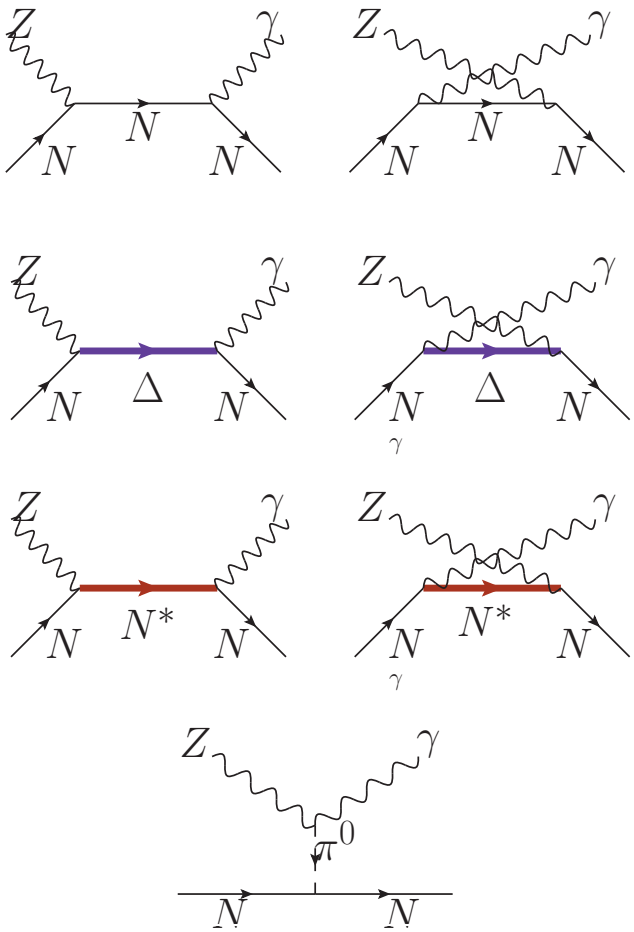
$$\nu(k) + N(p) \rightarrow \nu(k') + N(p') + \gamma(q_\gamma)$$

The amplitude is given by,

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

- the $\mp$ is for neutrino and antineutrino, respectively.
- $\epsilon_\mu^{*(\mathbf{r})}$ is the photon polarization vector.
- $\Gamma^{\mu\alpha}$ is the hadronic matrix element.

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 π 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,

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

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

Nucleon pole terms

The weak NC and EM currents:

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

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

The NC vector form factors:

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

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

- $F^{(p)}_{1,2}$ — (p, n) EM form factors
- $F^{(s)}_{1,2}$ — strange EM form factors, to be neglected!!!

$$F^{(N)}_1 = \frac{G^N_E + \tau G^N_M}{1+\tau}, \quad F^{(N)}_2 = \frac{G^N_M - G^N_E}{1+\tau}, \qquad N = p, n$$

Nucleon pole terms

The weak neutral current:

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

The NC axial form factors (dipole parametrization):

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

$$F_A(q^2) = g_A\left(1 - \frac{q^2}{M_A^2}\right)^{-2}$$

- $g_A = 1.267$, $m_A = 1.016$ GeV.
- $F_A^{(s)}$ — strange axial form factors, to be neglected!!!

$\Delta(1232)$ 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,

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

Γ_Δ is the resonance width.

$\Delta(1232)$ pole terms

The weak NC and EM currents are given by,

$$
\begin{aligned}
J^{\beta\mu}_{NC}(p,q) &= \left[\frac{\tilde{C}_3^V}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) + \frac{\tilde{C}_4^V}{M^2}(g^{\beta\mu}q\cdot p_\Delta - q^\beta p^\mu_\Delta)\right. \\
&+ \left.\frac{\tilde{C}_5^V}{M^2}(g^{\beta\mu}q\cdot p - q^\beta p^\mu)\right]\gamma_5 + \frac{\tilde{C}_3^A}{M}(g^{\beta\mu}\not{q} - q^\beta\gamma^\mu) \\
&+ \frac{\tilde{C}_4^A}{M^2}(g^{\beta\mu}q\cdot p_\Delta - q^\beta p^\mu_\Delta) + \frac{\tilde{C}_5^A}{M^2}g^{\beta\mu} + \frac{\tilde{C}_6^A}{M^2}q^\beta q^\mu,
\end{aligned}
$$

$$
\begin{aligned}
J^{\beta\mu}_{EM}(p,-q_\gamma) &= -\left[\frac{C_3^V}{M}(g^{\beta\mu}\not{q}_\gamma - q'^\beta_\gamma\gamma^\mu) + \frac{C_4^V}{M^2}(g^{\beta\mu}q_\gamma\cdot p_{\Delta c} - q^\beta_\gamma p^\mu_{\Delta c})\right. \\
&+ \left.\frac{C_5^V}{M^2}(g^{\beta\mu}q_\gamma\cdot p - q^\beta_\gamma p^\mu)\right]\gamma_5,
\end{aligned}
$$

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

$N - \Delta(1232)$ form factors

NC vector form factors and EM transition form factors:

- $\tilde{C}_i^V$ — NC vector form factors
- C_i^V — EM transition form factors

The NC vector form factors are related to the EM ones

$$\tilde{C}_i^V(q^2) = (1 - 2\sin^2\theta_W)\, C_i^V(q^2) \tag{1}$$

The EM form factors can be related to the helicity amplitudes $A_{1/2}$, $A_{3/2}$ and $S_{1/2}$.

The relation between EM form factors and helicity amplitudes

$N-\Delta$ EM form factor $\tilde{C}_i^V$ can be obtained from the helicity amplitudes, $A_{1/2}$, $A_{3/2}$ and $S_{1/2}$, which extracted from **pion photo- and electro-production**.

$$\mathcal{A}_{1/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle S_z^* = \frac{1}{2} \left| \epsilon_\mu^{(+)} J_{EM}^\mu \right| S_z = -\frac{1}{2} \right\rangle \frac{1}{\sqrt{2M}\sqrt{2M_R}},$$

$$\mathcal{A}_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle S_z^* = \frac{3}{2} \left| \epsilon_\mu^{(+)} J_{EM}^\mu \right| S_z = \frac{1}{2} \right\rangle \frac{1}{\sqrt{2M}\sqrt{2M_R}},$$

$$\mathcal{S}_{1/2} = -\sqrt{\frac{2\pi\alpha}{k_R}} \left\langle S_z^* = \frac{1}{2} \left| \frac{|\vec{k}|}{\sqrt{Q^2}} \epsilon_\mu^{(0)} J_{EM}^\mu \right| S_z = \frac{1}{2} \right\rangle \frac{1}{\sqrt{2M}\sqrt{2M_R}},$$

We adopt the parametrization of the helicity amplitude obtained in the **MAID** analysis.
(D. Drechsel, et al., EPJA 34(2007),69 and
`http://www.kph.uni-mainz.de/MAID`)

$N - \Delta(1232)$ form factors

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 of NCγ strongly depends on $C_5^A(q^2)$.

Off diagonal Goldberger-Treiman relations

The off diagonal GT relation amounts to

$$C_5^A(0) = -\sqrt{\frac{2}{3}}\frac{f^*}{m_\pi}f_\pi \tag{2}$$

The axial coupling $C_5^A(0)$ is now expressed in terms of f^*/m_π extracted from the $\Delta \to \pi N$ decay width.

- $C_5^A(0) = 1.0 \pm 0.11$ and $m_A = 0.93$ GeV, fitted to the ν-induced π production ($\nu_\mu p \to \mu^- p \pi^+$) ANL and BNL bubble chamber data.
  E. Hernandez, et al., PRD 81(2010), 085046.
- the uncertainties of our model mainly comes from the $C_5^A(0) = 1.0 \pm 0.11$.

t-channel π exchange term

The hadronic matrix element π pole term is given by,

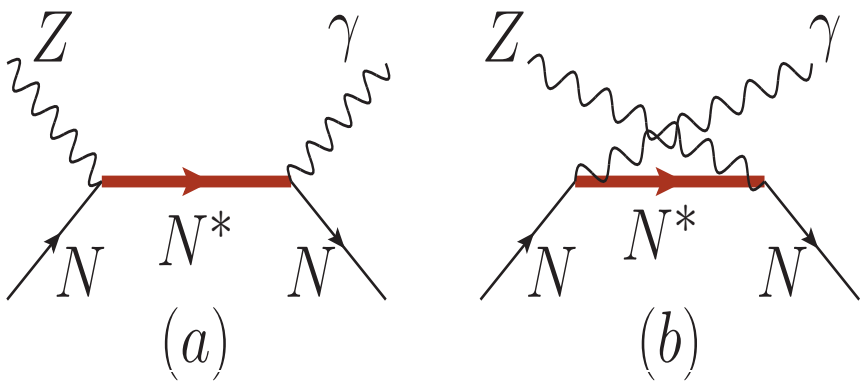
$$\Gamma^{\mu\alpha} = -i C_{p,n} \frac{g_A}{4\pi^2 f_\pi^2} \left(\frac{1}{2} - 2sin^2\theta_W \right) \epsilon^{\sigma\delta\mu\alpha} q_{\gamma\sigma} q_\delta (\not{p}' - \not{p}) \gamma_5 D_\pi(p' - p),$$

where,

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

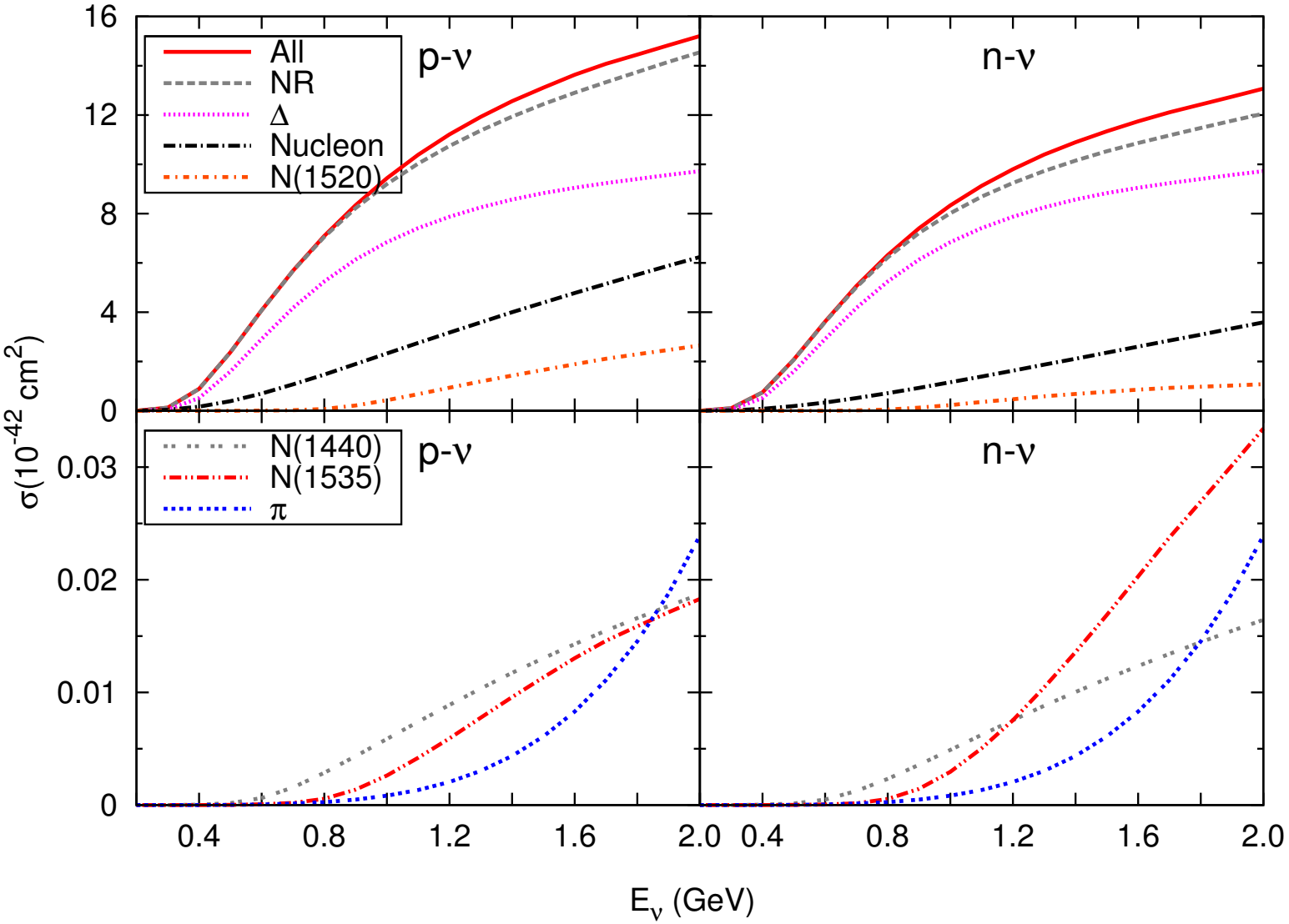
$$D_\pi(p) = \frac{1}{p^2 - m_\pi^2} \leftarrow \pi \text{ propagator}$$

N^* pole term [$N(1440)$, $N(1520)$ $N(1535)$]

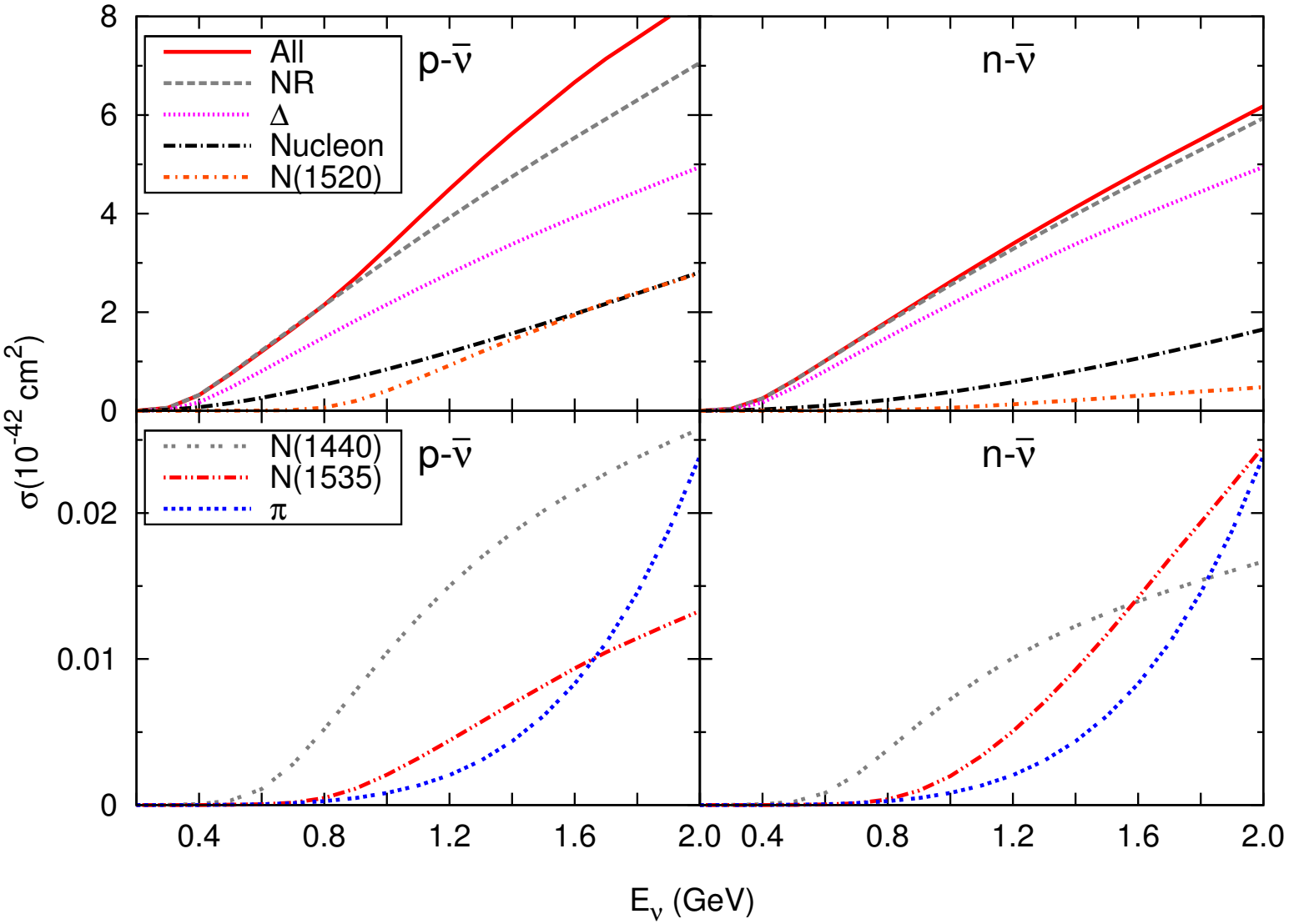


- The hadronic matrix elements of $N(1440)$, $N(1535)$ are similar to that of nucleon pole.
- the hadronic matrix elements of $N(1520)$ is similar to that of $\Delta(1232)$ pole terms.
- $N - N^*$ vector form factors can be obtained from helicity amplitudes.
- We have assumed a standard dipole form for the axial form factors.
- The axial couplings are obtained by the off diagonal Goldberger-Treiman relations.

NCγ cross section on the nucleon for **neutrino**



The cross section of NCγ on nucleon for antineutrino



Incoherent NCγ on nuclei

NCγ on nuclei

It consists of the incoherent and coherent reactions.

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

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

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

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,

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

- Relativistic Local Fermi Gas: $k_F(\vec{r}) = \left[3\pi^2\rho(\vec{r})\right]^{1/3}$
- Fermi motion: $n(\vec{r},\vec{p}) = \Theta(k_F(\vec{r}) - |\vec{p}|)$
- Pauli blocking: $1 - n(\vec{r},\vec{p})$

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 modification of the $\Delta(1232)$ resonance

For propagator D_Δ is,

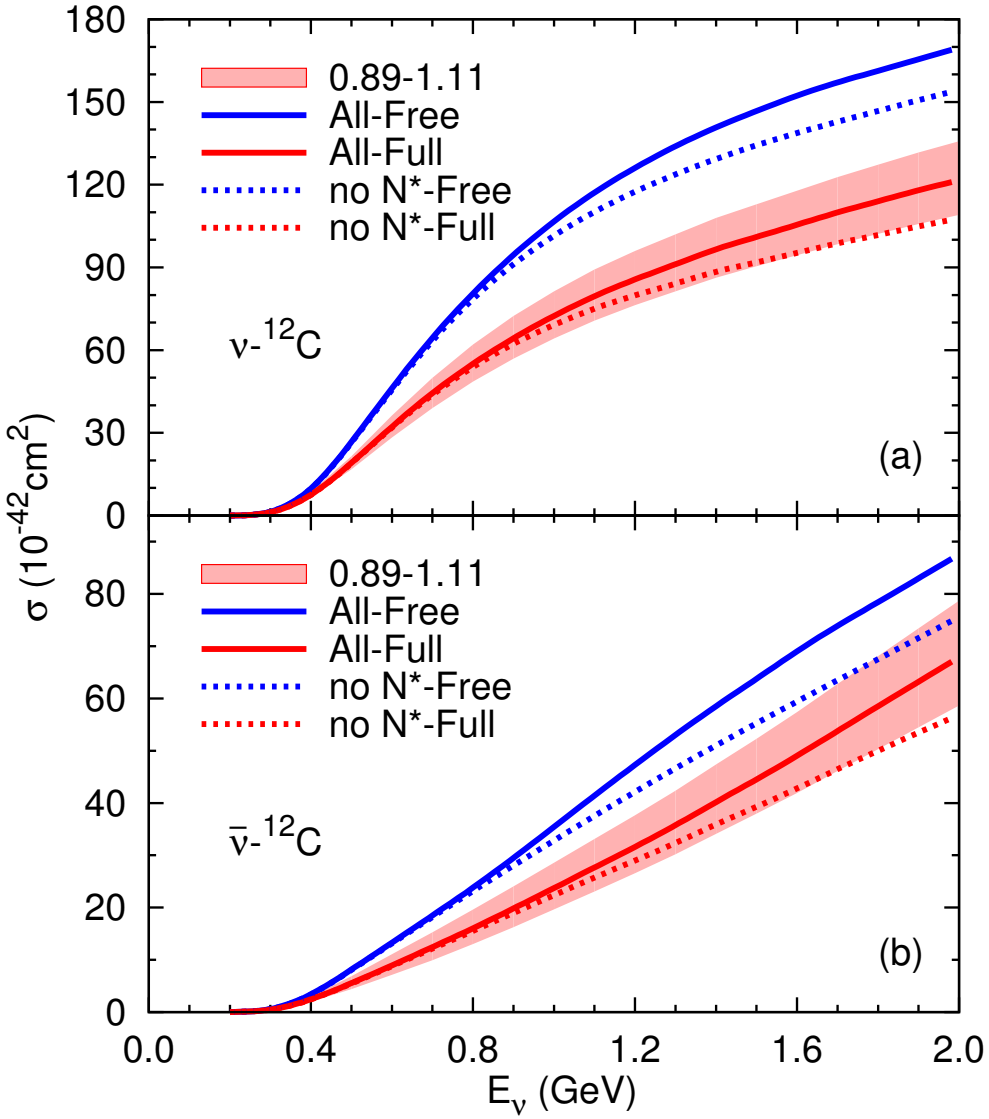
$$D_\Delta(p) = \frac{1}{p^2 - {M_\Delta}^2 + iM_\Delta\Gamma_\Delta(p^2)},$$

Replace

- $\Gamma_\Delta/2 \to \Gamma_\Delta^{\rm Pauli}/2 - {\rm Im}\Sigma_\Delta(\rho)$
- $\Gamma_\Delta^{\rm Pauli}$ — free width of $\Delta \to N\pi$ modified by Pauli blocking
- ${\rm Im}\Sigma_\Delta(\rho)$, including many body process: $\Delta N \to NN$, $\Delta N \to NN$ and $\Delta NN \to NNN$

E. Oset and L. Salcedo, NPA 468(1987), 631.

Incoherent reaction



Coherent NCγ on nuclei

Coherent reaction

The amplitude is given by,

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

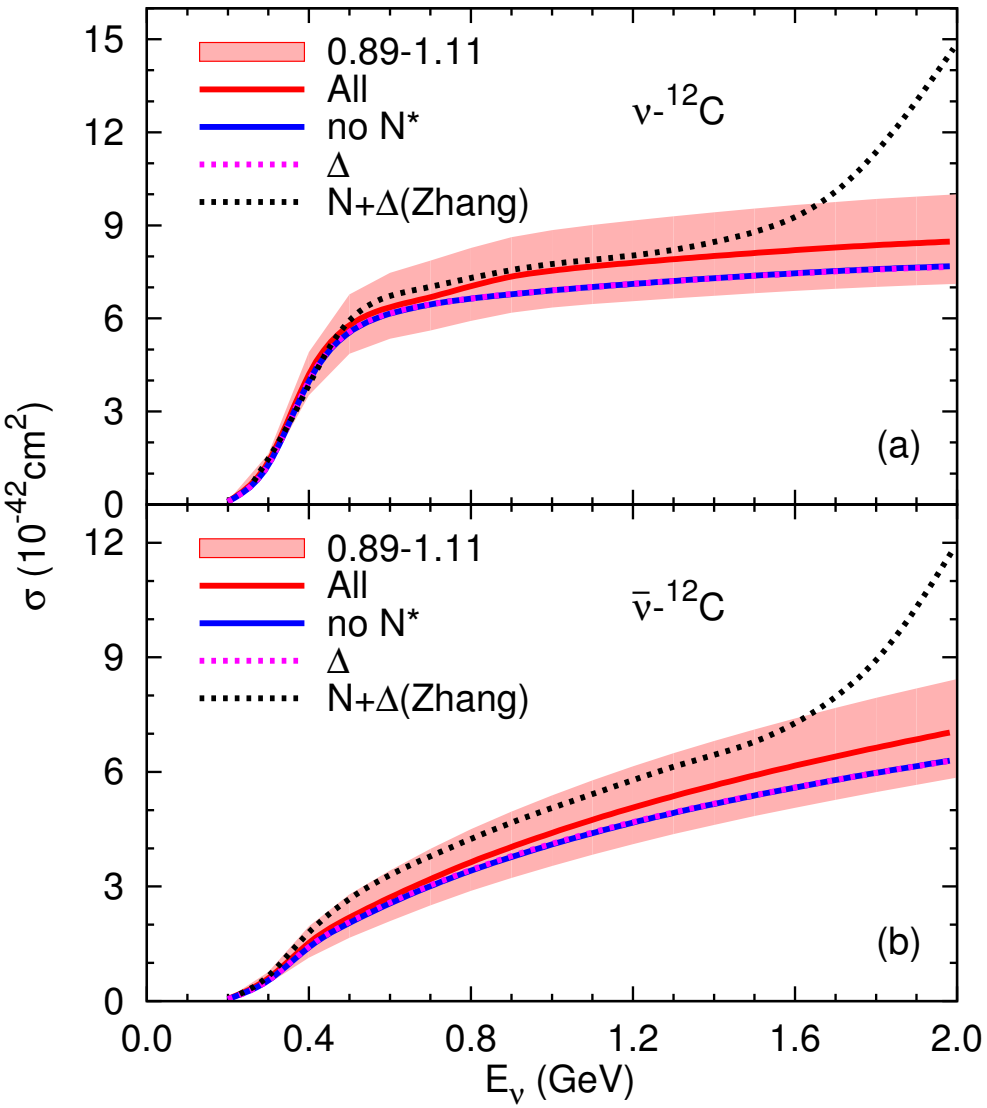
the hadronic current $J^\alpha_{coh(r)}$ is given by,

$$J^\alpha_{coh(r)} = ie\epsilon^{*(r)}_\mu \int d^3\vec{r}\, e^{i(\vec{q}-\vec{q}_\gamma)\cdot\vec{r}} (\rho_p \Gamma^{\mu\alpha}_p + \rho_n \Gamma^{\mu\alpha}_n)$$

- nuclear correction: $\Gamma_\Delta/2 \to \Gamma^{\text{Pauli}}_\Delta/2 - \text{Im}\Sigma_\Delta(\rho)$
- coherent sum of all nucleons:

$$\Gamma^{\mu\alpha}_N = \frac{1}{2}\sum_i \text{Tr}\left[\bar{u}\Gamma^{\mu\alpha}_{i,N} u\right] \quad (3)$$

Coherent reaction



Comparison with MiniBooNE Estimates

CCQE reconstructed (anti)neutrino energy

Assuming that the visible energy (E_e) is generated by an electron from $\nu_e + n \rightarrow p + e^-$ in a bound proton/neutron at rest, 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. The binding energy $E_B = 34$ MeV.
(A. Aguilar-Arevalo et al., PRD 84(2011), 072005)

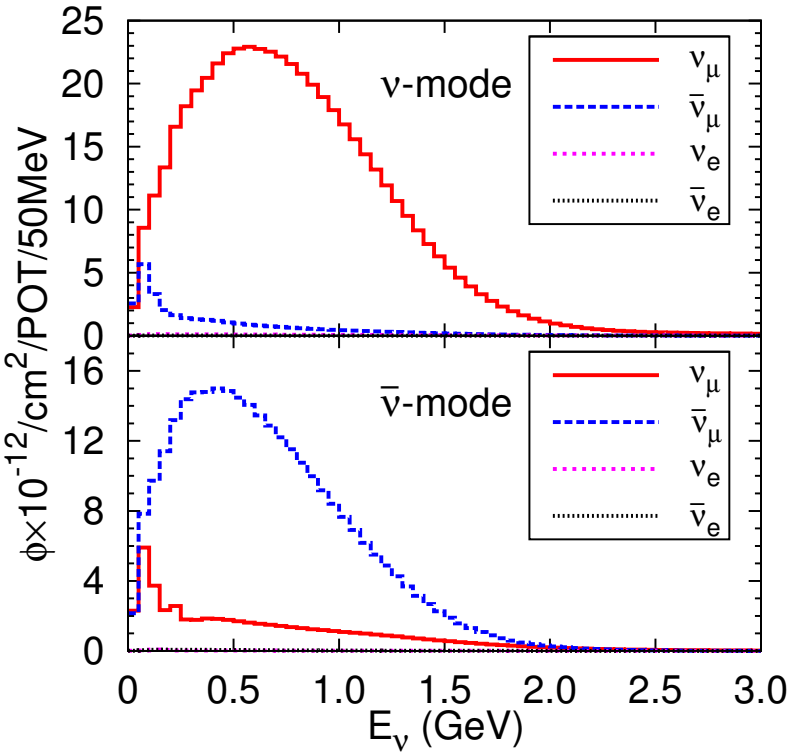
The events

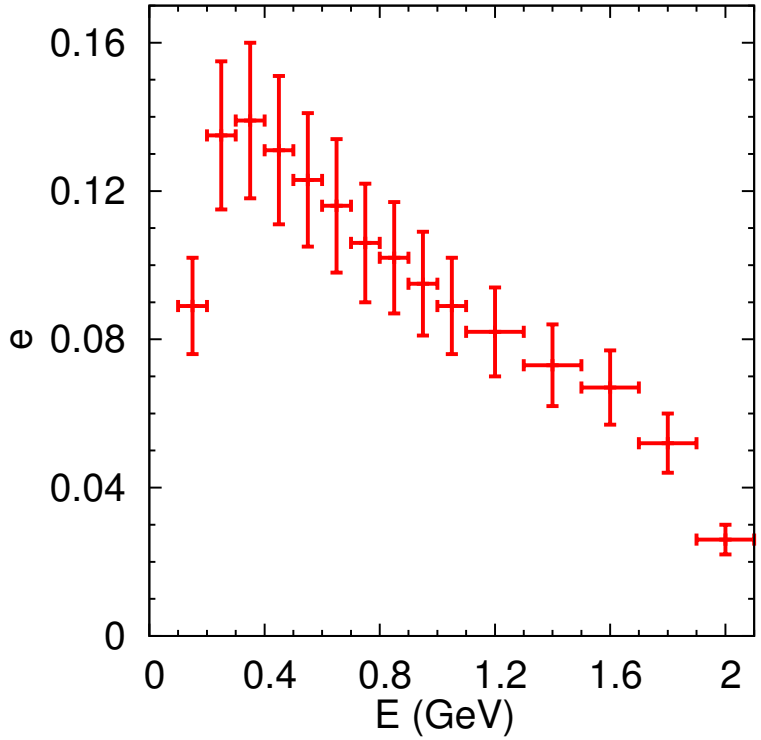
NCγ events at the MiniBooNE detector is given by,

$$\frac{dN}{dE_\gamma d\cos\theta_\gamma} = \varepsilon(E_\gamma) \sum_{l=\nu_\mu,\bar{\nu}_\mu} N_{\rm POT}^{(l)} \times \sum_{t=p,\,^{12}{\rm C}} N_t \int dE_\nu \phi_l(E_\nu) \frac{d\sigma_{l\,t}(E_\nu)}{dE_\gamma d\cos\theta_\gamma} .$$

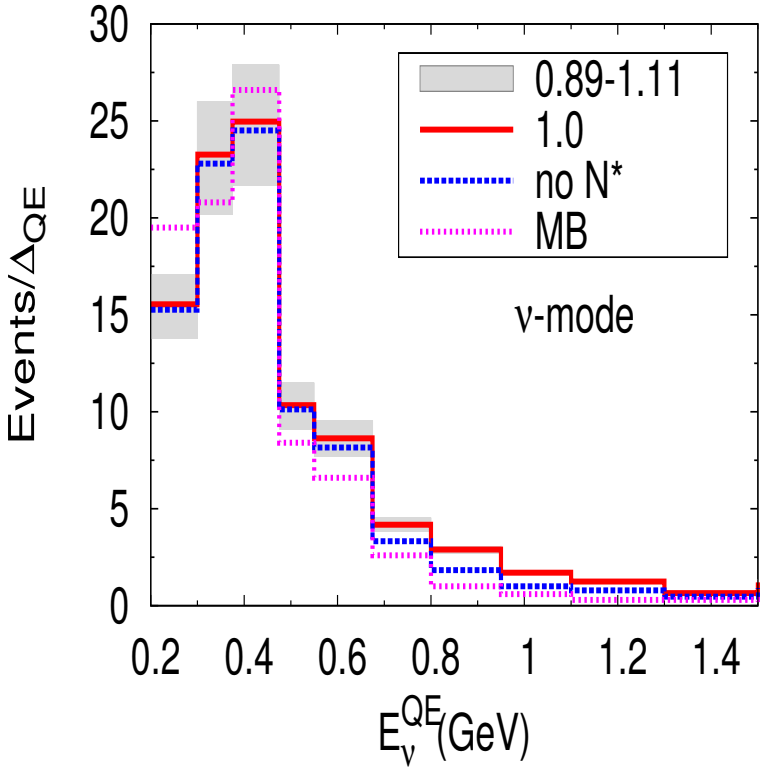
- $d\sigma_{l\,t}(E_\nu)/(dE_\gamma d\cos\theta_\gamma)$: cross section for NC$\gamma$ on proton, incoherent and coherent reaction on Carbon
- $N_{\rm POT}^{(l)}$: the total number of protons on target (POT) $N_{\rm POT}^{\nu} = 6.46 \times 10^{20}$ and $N_{\rm POT}^{\bar{\nu}} = 11.27 \times 10^{20}$
- N_t: the number of protons/carbon nuclei in the target (806 tons CH_2)
- $\varepsilon(E_\gamma)$: energy dependent detection efficiency
- $\phi_l(E_\nu)$: neutrino/antineutrino fluxes

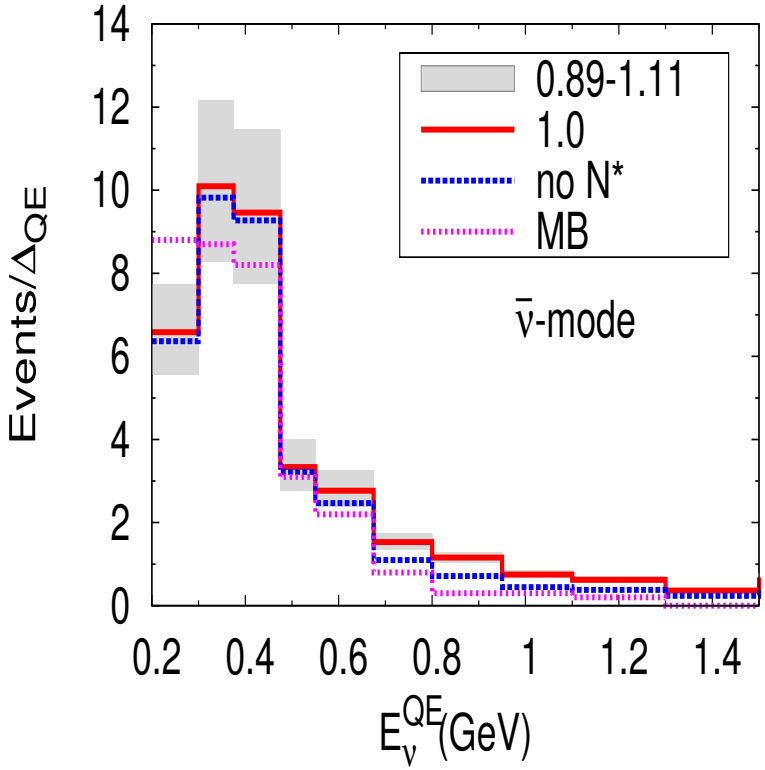
Beam flux and detection efficiency at MiniBooNE



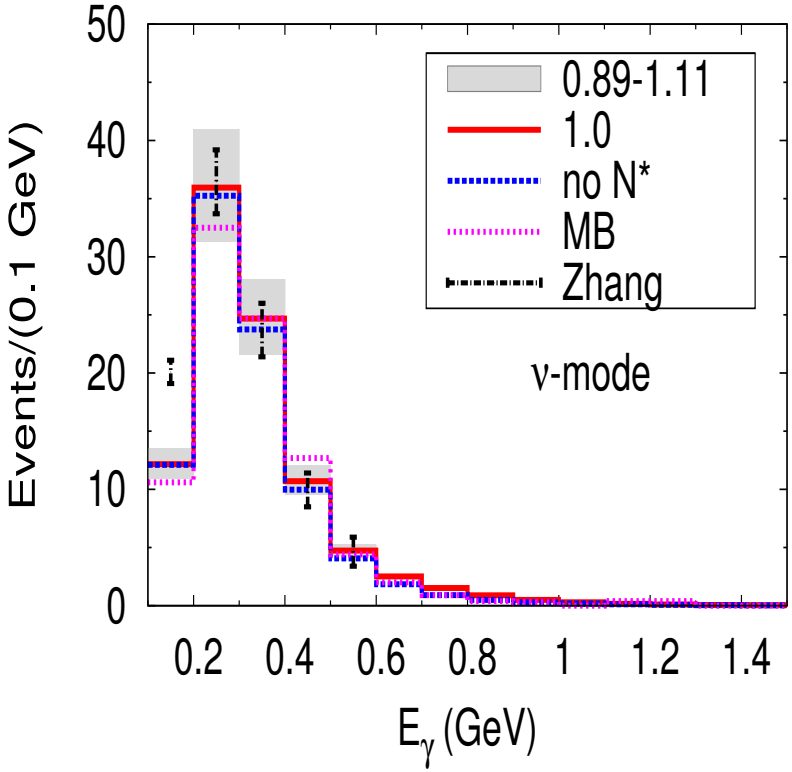


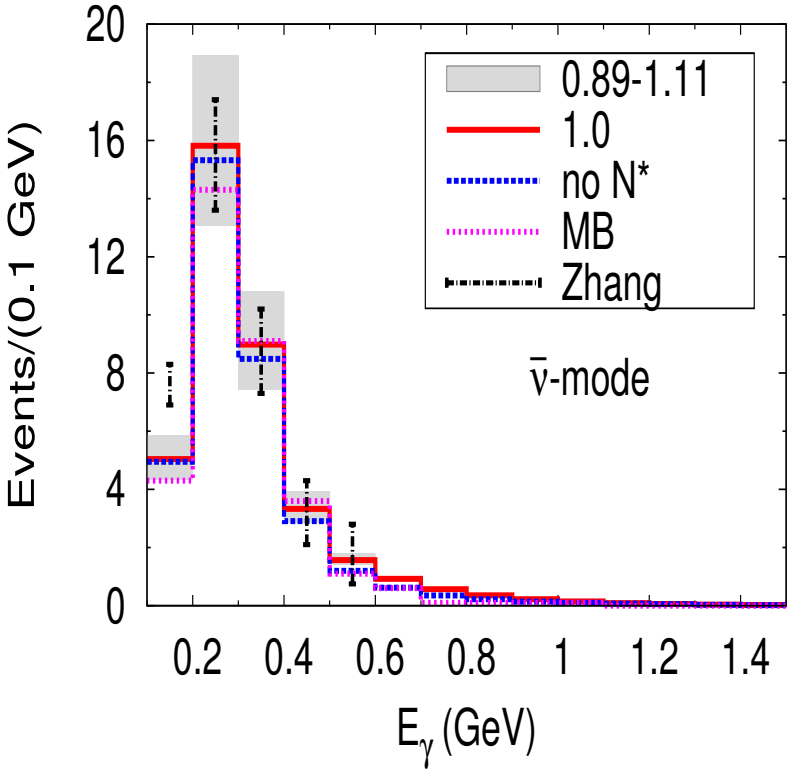
Comparison to the MB estimate



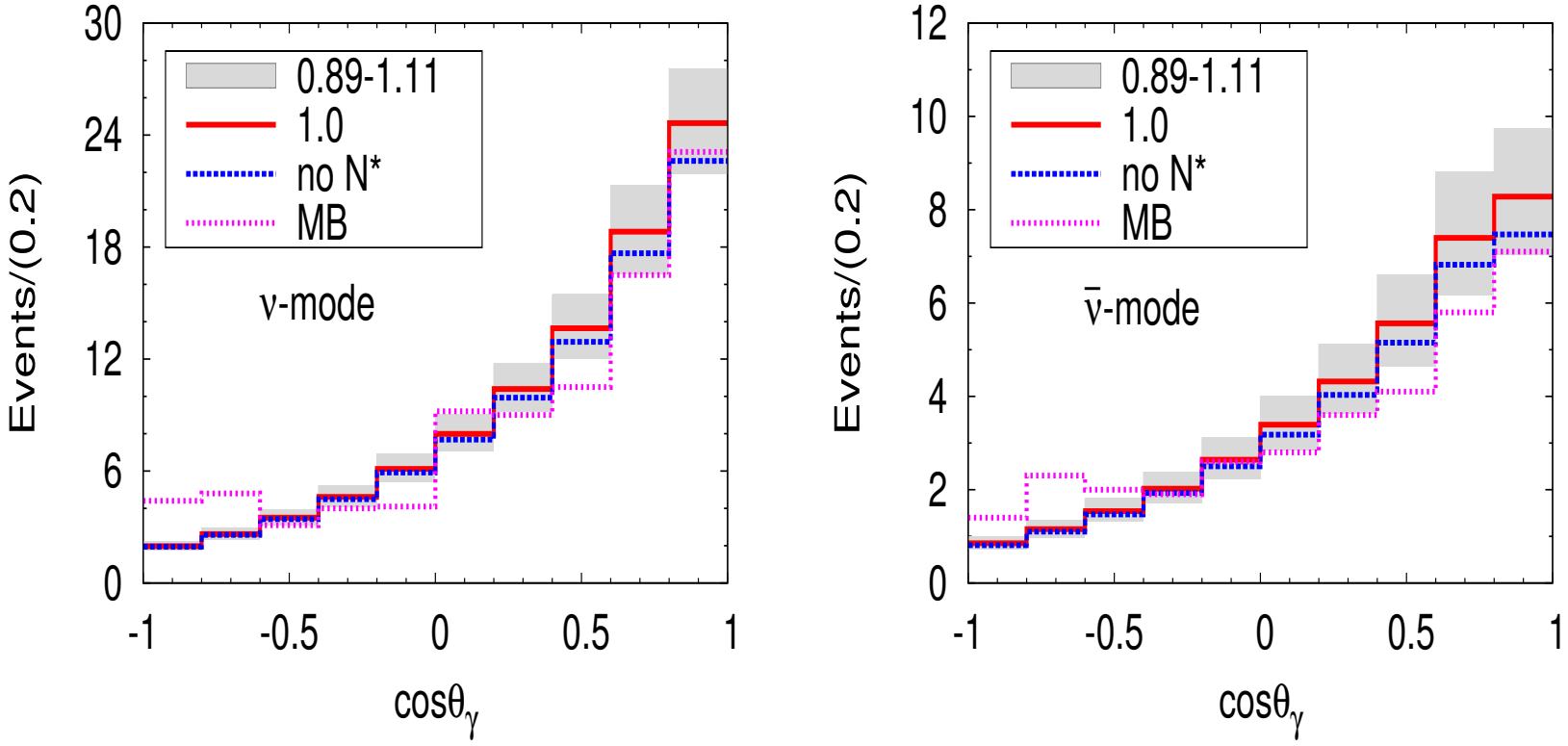


E_γ distribution of the photon events





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



Summary

Summary

- We have studied NCγ on nucleons and nuclei in the intermediate energy region ($E_\nu \sim 1$ Gev).
- Our model consists of nucleon pole, Δ pole, heavier resonances pole and t-channel pion-exchange.
- Large reduction ($\sim 30\%$) on the cross section due to nuclear effects — Fermi motion, Pauli blocking and in-medium modification of Δ resonance.
- Theoretical error dominated by $N - \Delta$ axial transition properties.

- Our prediction is consistent with MiniBooNE estimate.
- NCγ: insufficient to explain the excess of e-like events at MiniBooNE.

Thank you!