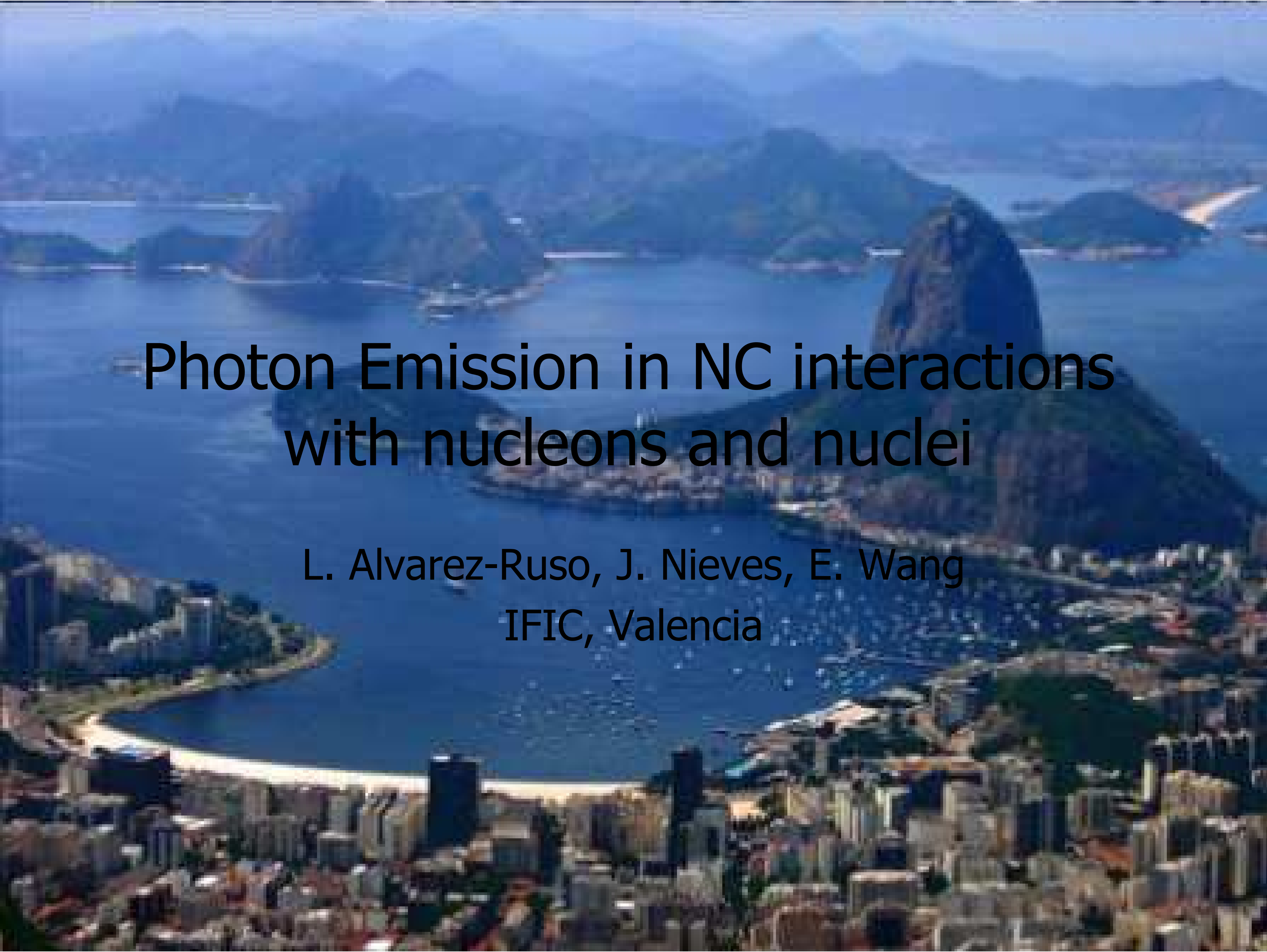


Photon Emission in NC interactions with nucleons and nuclei

L. Alvarez-Ruso, J. Nieves, E. Wang
IFIC, Valencia

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

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

    Ankowski et al., PRL 108 (2012), 052505 $\quad A'^{*} \to \gamma\, A$

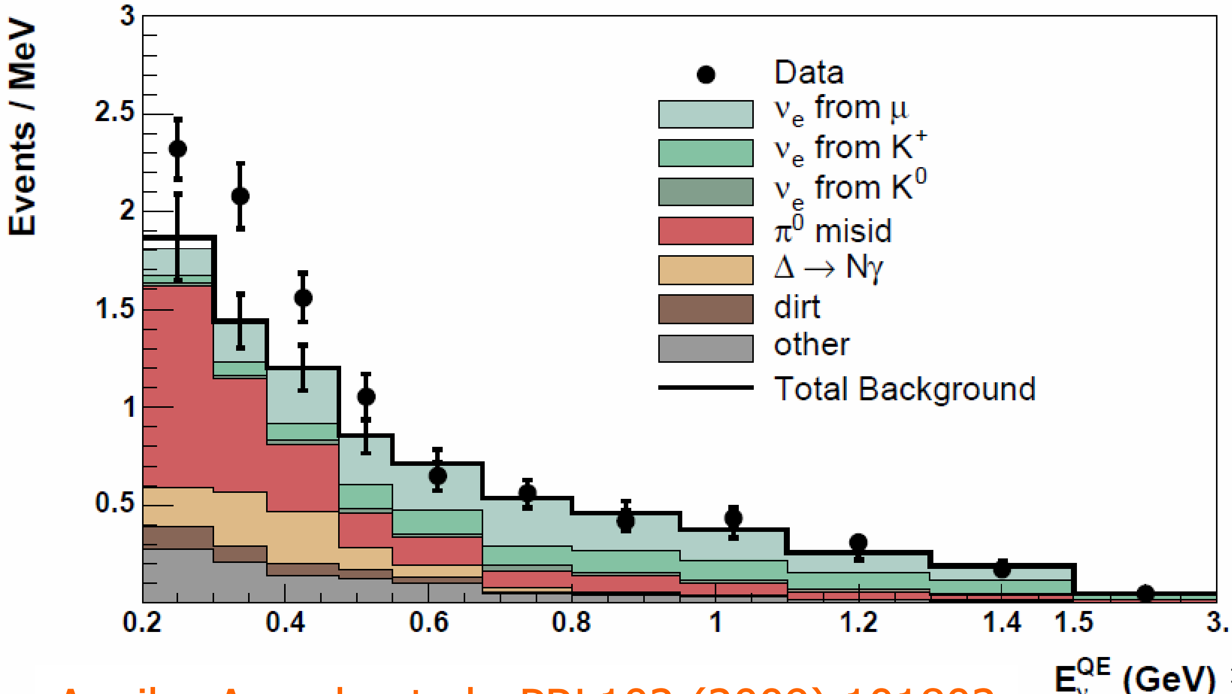
  - Small cross section (weak & e.m.)

  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 $\nu_\mu \to \nu_e$ search:



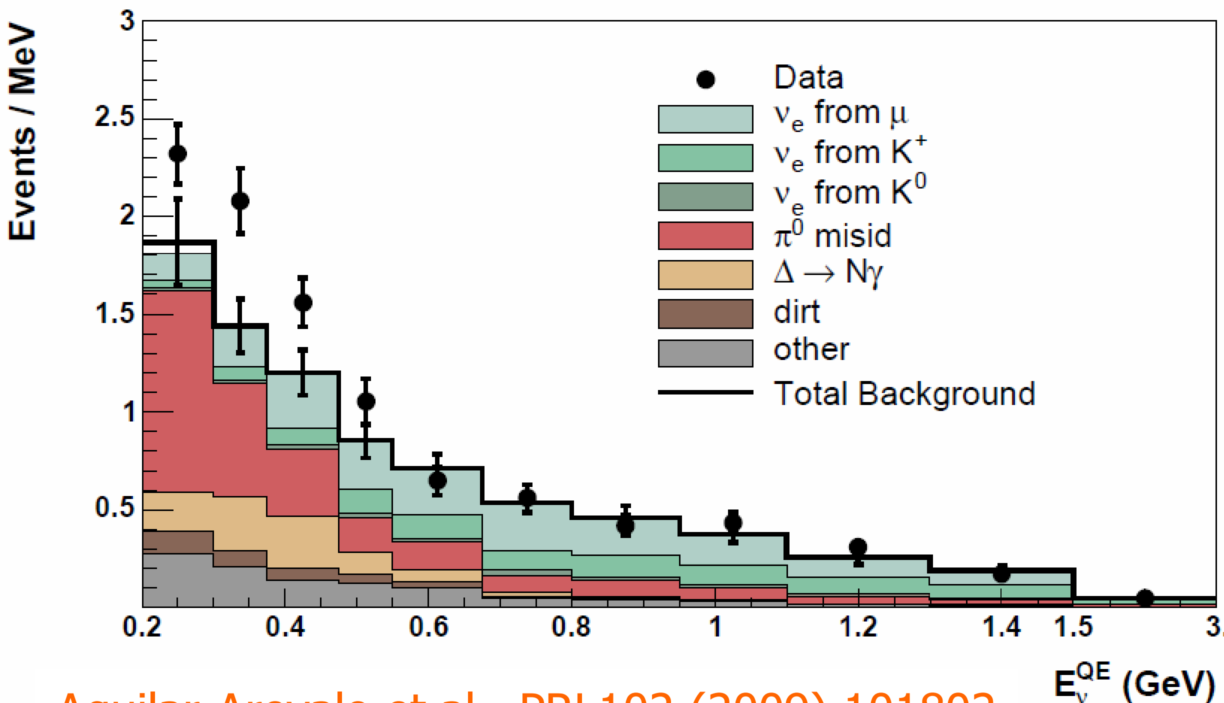
Aguilar-Arevalo et al., PRL102 (2009) 101802

reconstructed ν energy

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

Introduction

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



Aguilar-Arevalo et al., PRL102 (2009) 101802

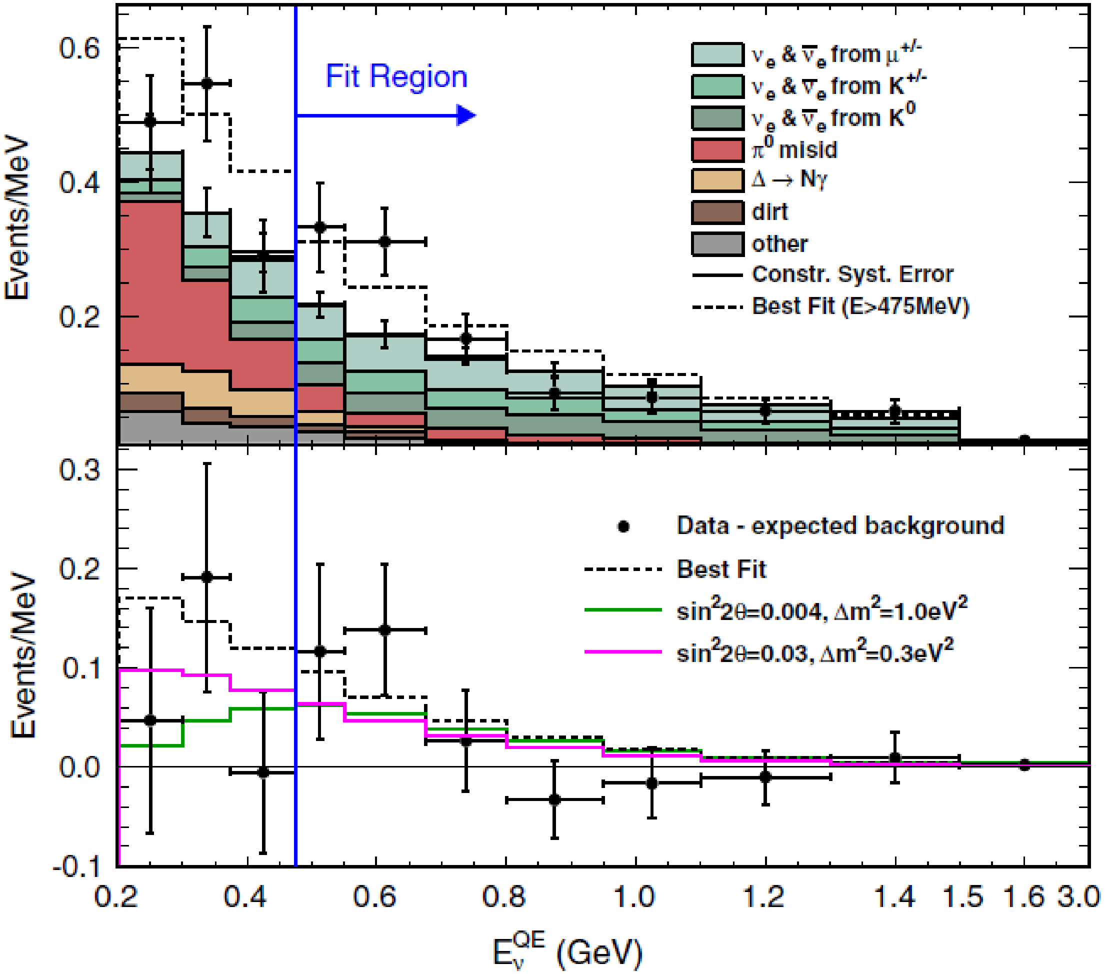
TABLE I. The expected number of events in the $200 < E_\nu^{QE} <$ 300 MeV, $300 < E_\nu^{QE} < 475$ MeV, and $475 < E_\nu^{QE} <$ 1250 MeV energy ranges from all of the backgrounds after the complete event selection of the final analysis.

Process	200–300	300–475	475–1250
ν_μ CCQE	9.0	17.4	11.7
$\nu_\mu e \to \nu_\mu e$	6.1	4.3	6.4
NC π^0	103.5	77.8	71.2
NC $\Delta \to N\gamma$	19.5	47.5	19.4
External events	11.5	12.3	11.5
Other events	18.4	7.3	16.8
ν_e from μ decay	13.6	44.5	153.5
ν_e from K^+ decay	3.6	13.8	81.9
ν_e from K_L^0 decay	1.6	3.4	13.5
Total background	186.8 ± 26.0	228.3 ± 24.5	385.9 ± 35.7

- Unexplained excess of events at $200 < E_\nu^{QE} < 475$ 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
  - Shape of event excess consistent with NC π^o & NC $\Delta \to$ N γ

Introduction

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



Aguilar-Arevalo et al., PRL105 (2010) 181801

- Excess of events at $E_\nu{}^{QE}$ > 475 MeV consistent with LSND
- Excess of events at 200 < $E_\nu{}^{QE}$ < 475 MeV absent only if oscillations are considered

Introduction

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

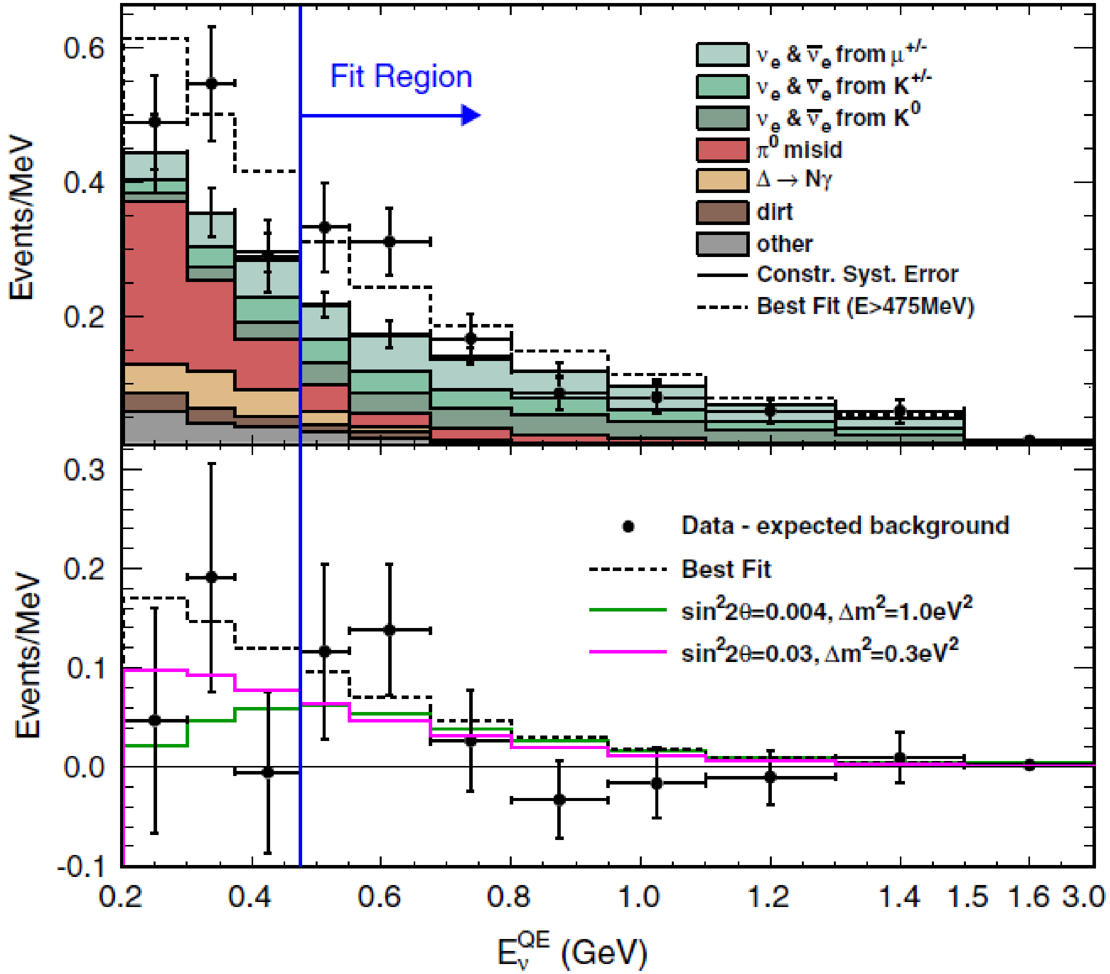


TABLE I. The expected (unconstrained) number of events for different E_ν^{QE} ranges from all of the backgrounds in the $\bar{\nu}_e$ appearance analysis and for the LSND expectation (0.26% oscillation probability averaged over neutrino energy) of $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, for 5.66×10^{20} POT.

Process	200–475 MeV	475–1250 MeV
ν_μ & $\bar{\nu}_\mu$ CCQE	4.3	2.0
NC π^0	41.6	12.6
NC $\Delta \to N\gamma$	12.4	3.4
External events	6.2	2.6
Other ν_μ & $\bar{\nu}_\mu$	7.1	4.2
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ decay	13.5	31.4
ν_e & $\bar{\nu}_e$ from $K^\pm$ decay	8.2	18.6
ν_e & $\bar{\nu}_e$ from K_L^0 decay	5.1	21.2
Other ν_e & $\bar{\nu}_e$	1.3	2.1
Total background	99.5	98.1
0.26% $\bar{\nu}_\mu \to \bar{\nu}_e$	9.1	29.1

Aguilar-Arevalo et al., PRL105 (2010) 181801

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

Introduction

- Microscopic model, R. Hill, PRD 81 (2010)
  - 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
- Comparison to MiniBooNE, R. Hill, PRD 84 (2011)
- Assumptions:
  - Detector mass: 800x10^6 g
  - 6.46x10^{20} POT (ν) and 5.76x10^{20} POT ($\bar{\nu}$)
  - Cut E_γ > 140 MeV
  - Efficiency: 25 %

Introduction

- Microscopic model, R. Hill, PRD 81 (2010)
  - 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
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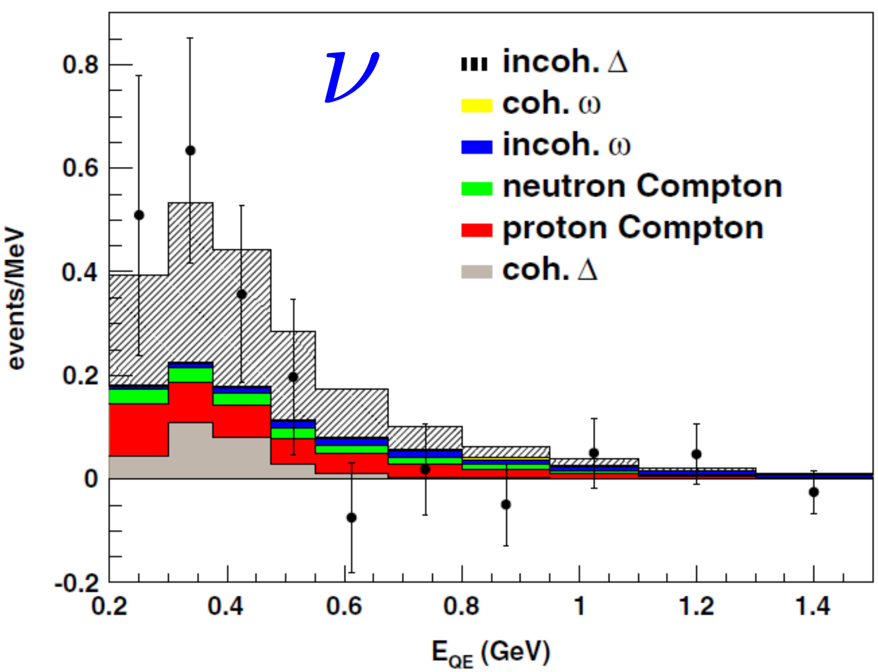
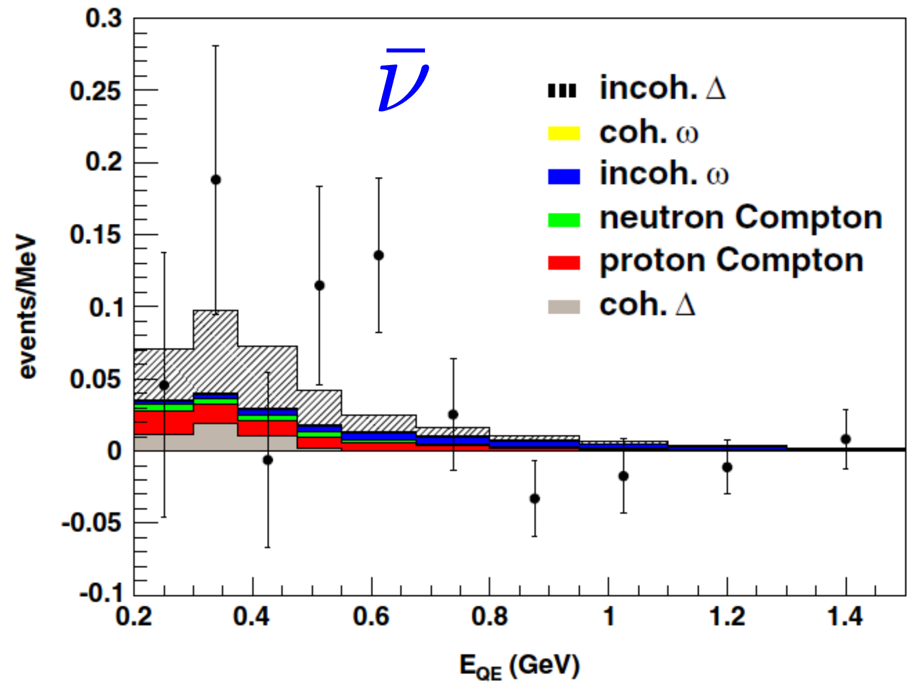
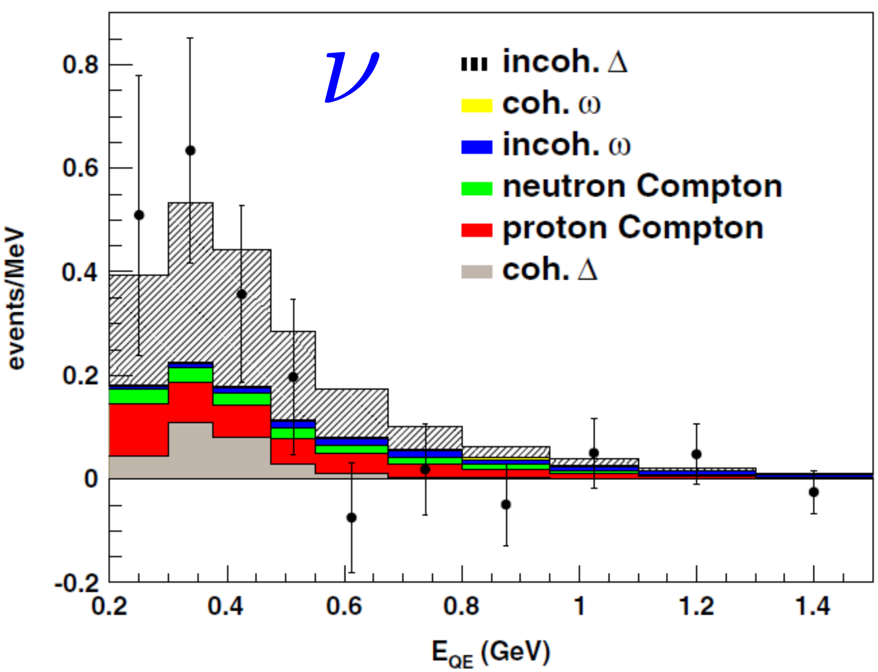


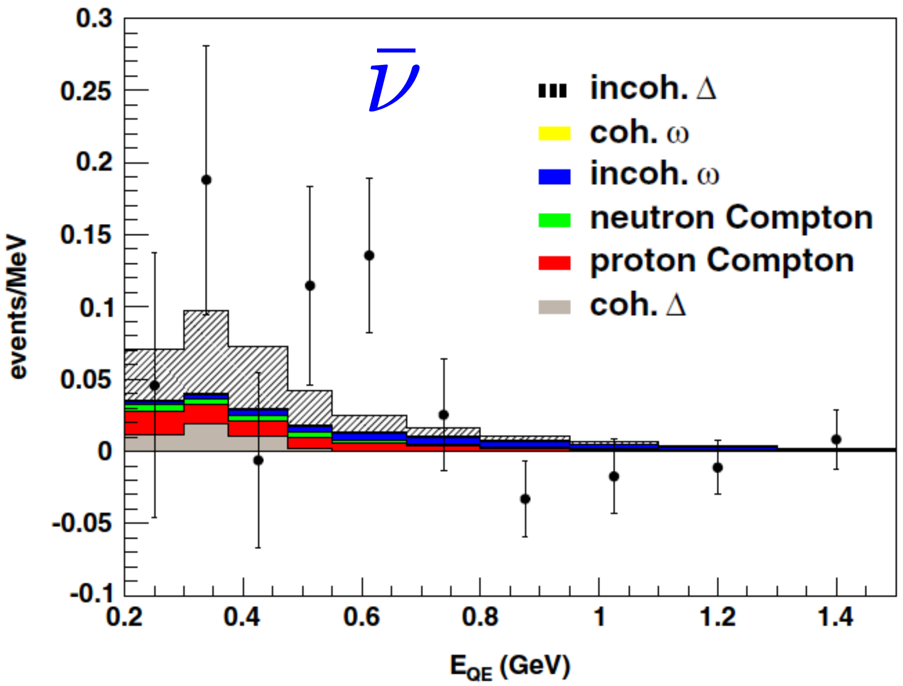


- $\Delta \rightarrow N \gamma$ events: twice the MiniBooNE estimate
- Conclusion: Neglected events give a significant contribution to the MiniBooNE low-energy excess

Introduction

- Microscopic model, R. Hill, PRD 81 (2010)
  - 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
- Comparison to MiniBooNE, R. Hill, PRD 84 (2011)

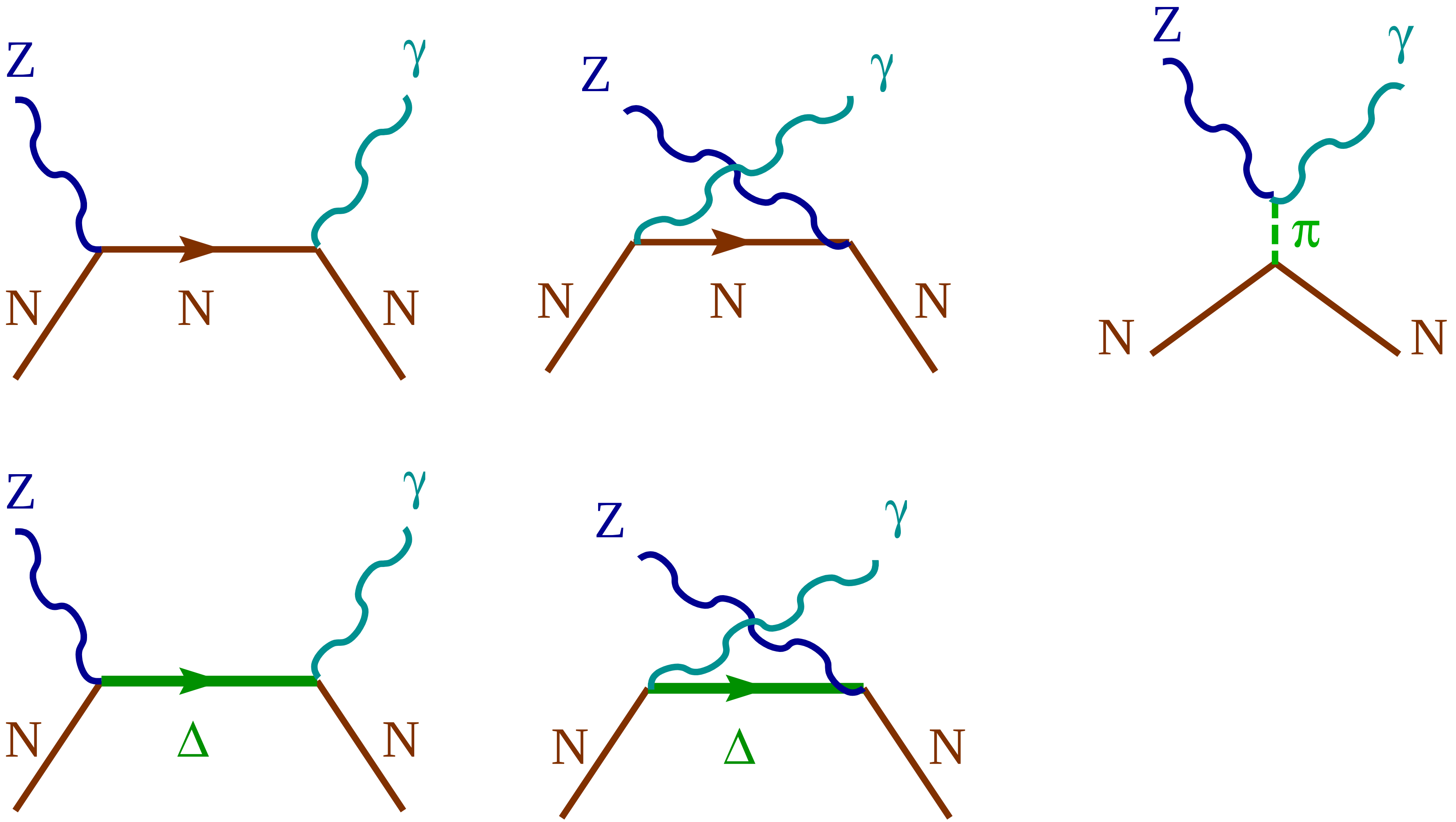




- However, nuclear corrections have not been considered ($CH_2 \approx$ 8p6n)

The model

- Feynman diagrams:



The model

- Amplitude:

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

$G_F \leftarrow$ Fermi constant

$e \leftarrow$ electric charge

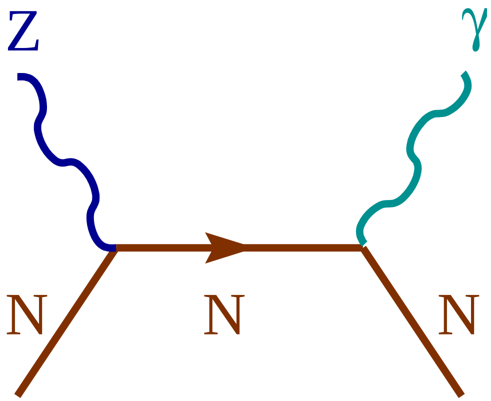
$\epsilon_\mu^{*(r)} \leftarrow$ photon polarization

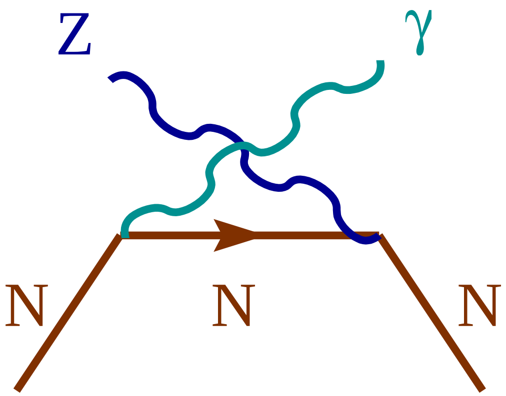
$l_\alpha \leftarrow$ NC for ν or $\bar{\nu}$

$\Gamma^{\mu\alpha} \leftarrow$ specific for each mechanism

The model

- Nucleon pole terms:





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

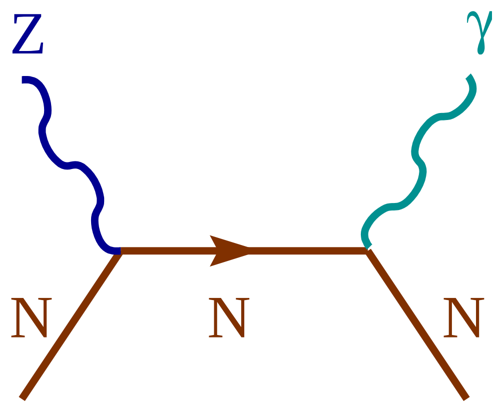
q $\leftarrow$ 4-momentum transferred to the nucleon

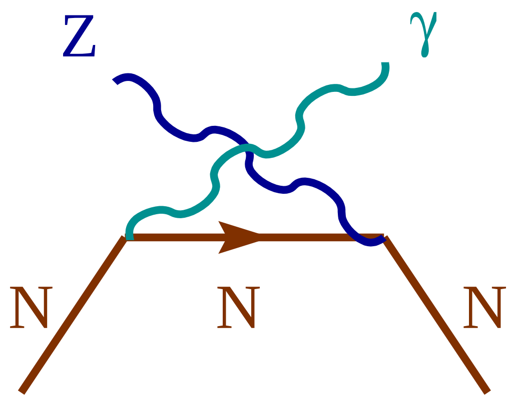
q_γ $\leftarrow$ photon 4-momentum

$$D_N(p) = \frac{1}{\not{p} - m_N}$$ $\leftarrow$ nucleon propagator

The model

- Nucleon pole terms:





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

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

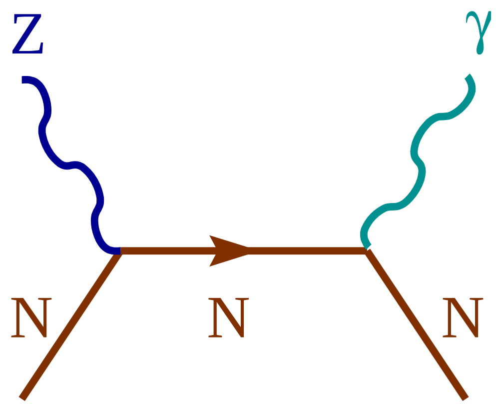
- Vector NC form factors:

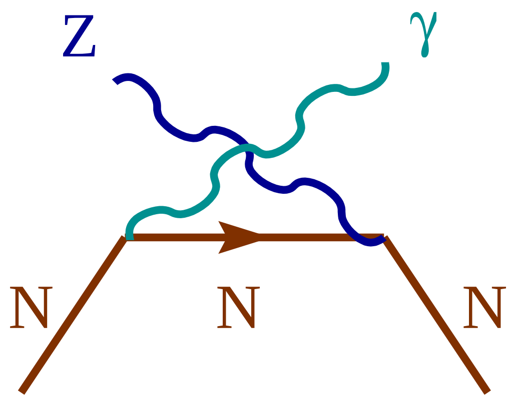
$$2\tilde{F}^{(p)}_{1,2} = (1 - 4\sin^2\theta_W) F^{(p)}_{1,2} - F^{(n)}_{1,2} - F^{(s)}_{1,2}$$

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

  - $F^{(p,n)}_{1,2} \leftarrow$ p,n EM form factors (dipole parametrizations)
  - $F^{(s)}_{1,2} \leftarrow$ strange EM form factors $\rightarrow$ 0

- Nucleon pole terms:





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

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

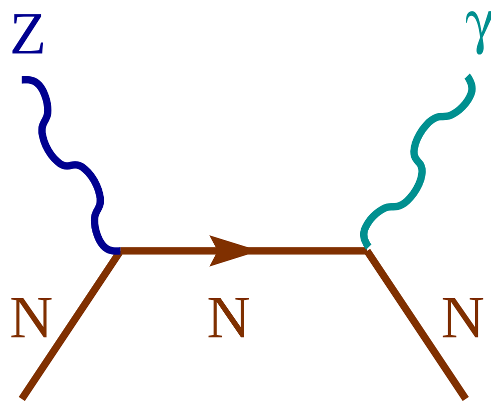
- Axial NC form factor:

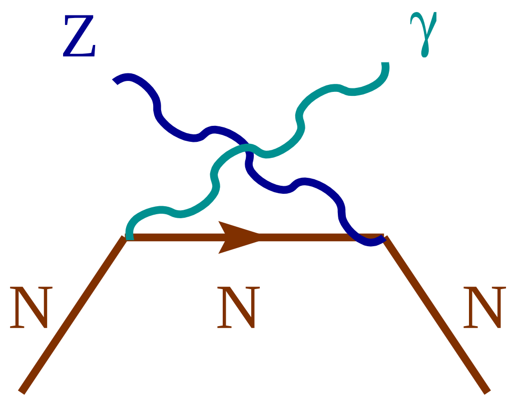
$$2\tilde{F}_A^{(p,n)} = \pm F_A + F_A^{(s)} \quad F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

  - g_A = 1.267, M_A= 1.016 GeV
  - $F_A^{(s)}$ $\leftarrow$ strange axial form factors $\rightarrow$ 0

The model

- Nucleon pole terms:





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

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

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

The model

- $\Delta(1232)$ pole terms:

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

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

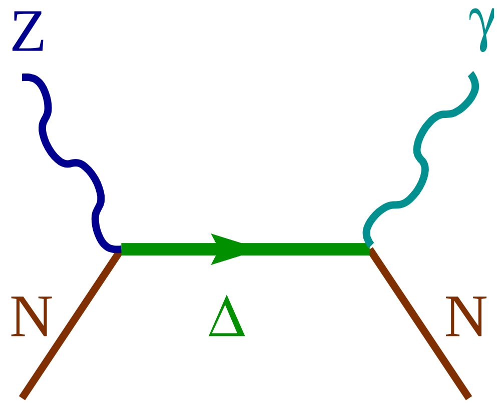
$$D^{\Delta}_{\delta\sigma}(p) = \frac{\Lambda_{\delta\sigma}}{p^2 - m_\Delta^2 + i m_\Delta \Gamma_\Delta(p^2)}$$ ← Delta propagator

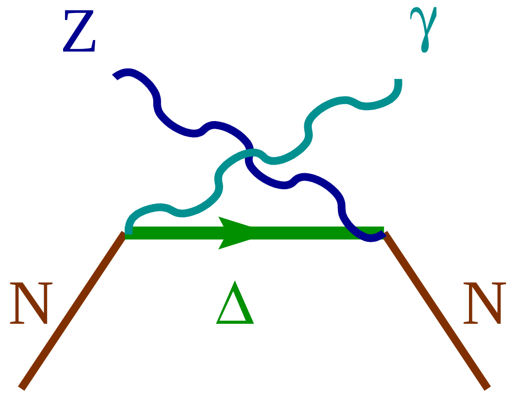
$$\Lambda_{\delta\sigma}$$ ← N-Δ projector

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

The model

- $\Delta(1232)$ pole terms:





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

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

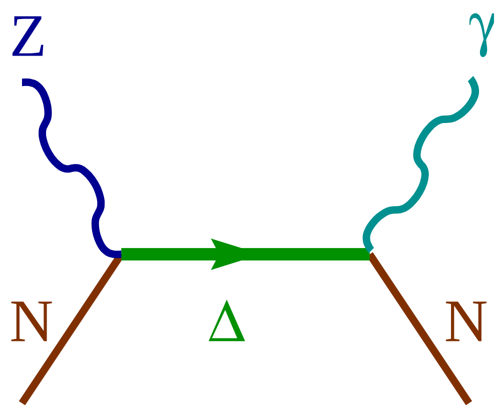
$$J^{\beta\mu}_{\mathrm{EM}}(p,q_\gamma) = \left[\frac{C^{(p,n)}_3(0)}{M}(g^{\beta\mu}\not{q}_\gamma - q^\beta_\gamma\gamma^\mu) + \frac{C^{(p,n)}_4(0)}{M^2}(g^{\beta\mu} q_\gamma\cdot p_\Delta - q^\beta_\gamma p^\mu_\Delta) + \frac{C^{(p,n)}_5(0)}{M^2}(g^{\beta\mu} q_\gamma\cdot p - q^\beta_\gamma p^\mu)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

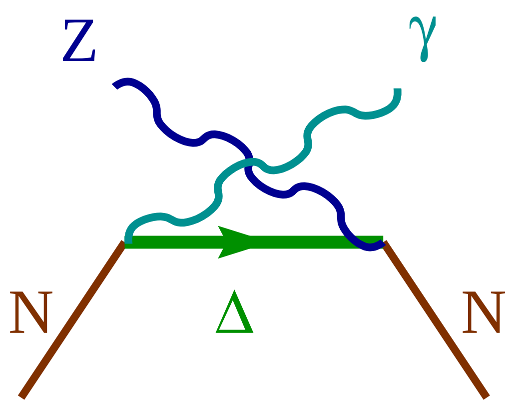
$$\tilde{C}^V_i = -(1 - 2\sin^2\theta_W) C^V_i \qquad C^{(p,n)}_i = -C^V_i$$

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

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

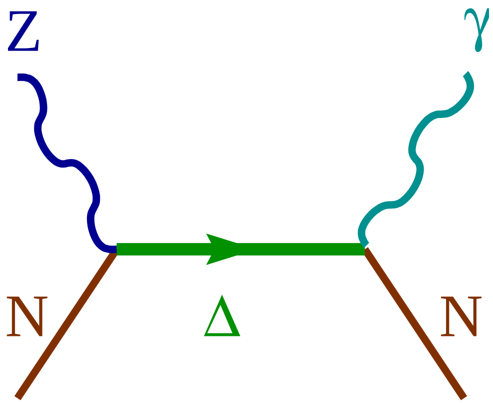
$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 1/2 \left| \epsilon^+_\mu J^\mu_{\mathrm{EM}} \right| N, J_z = -1/2 \right\rangle \zeta$$

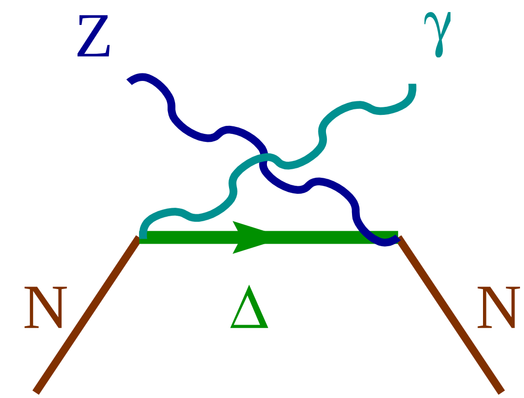
$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 3/2 \left| \epsilon^+_\mu J^\mu_{\mathrm{EM}} \right| N, J_z = 1/2 \right\rangle \zeta$$

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

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
  - Here we have adopted: Lalakulich, Paschos, PRD 71 (2005)

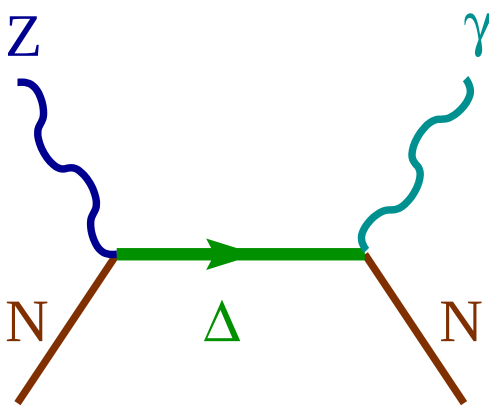
$$C_3^V = 2.13 \left(1 - \frac{q^2}{4m_V^2}\right)^{-1} D_V(q^2) \qquad D_V = \left(1 - \frac{q^2}{m_V^2}\right)^{-2}$$

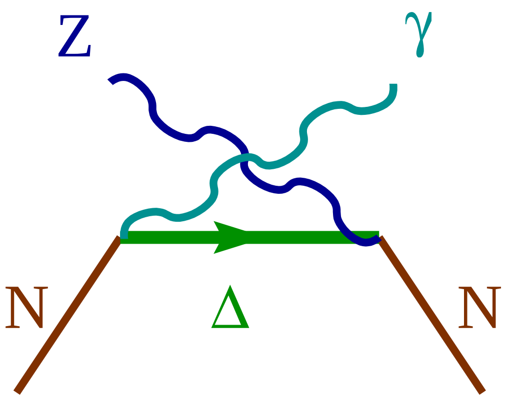
$$C_4^V = -1.51 \left(1 - \frac{q^2}{4m_V^2}\right)^{-1} D_V(q^2) \qquad m_V = 0.8 \text{ GeV}$$

$$C_5^V = 0.48 \left(1 - \frac{q^2}{0.776 m_V^2}\right)^{-1} D_V(q^2)$$

The model

- $\Delta(1232)$ pole terms:





- N-Δ Axial form factors C_i^A

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

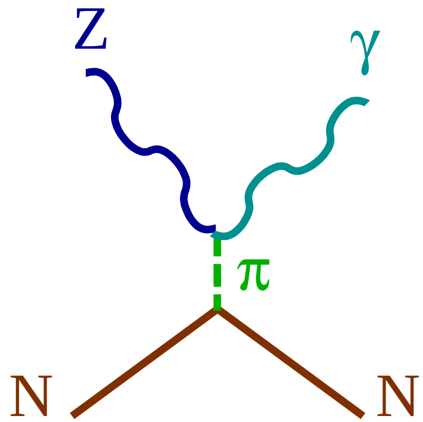
$$C_5^A = C_5^A(0) \left(1 + \frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$$

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

    Hernandez et al., PRD 81 (2010)

The model

- π pole term:



- from the anomalous part of the Lagrangian

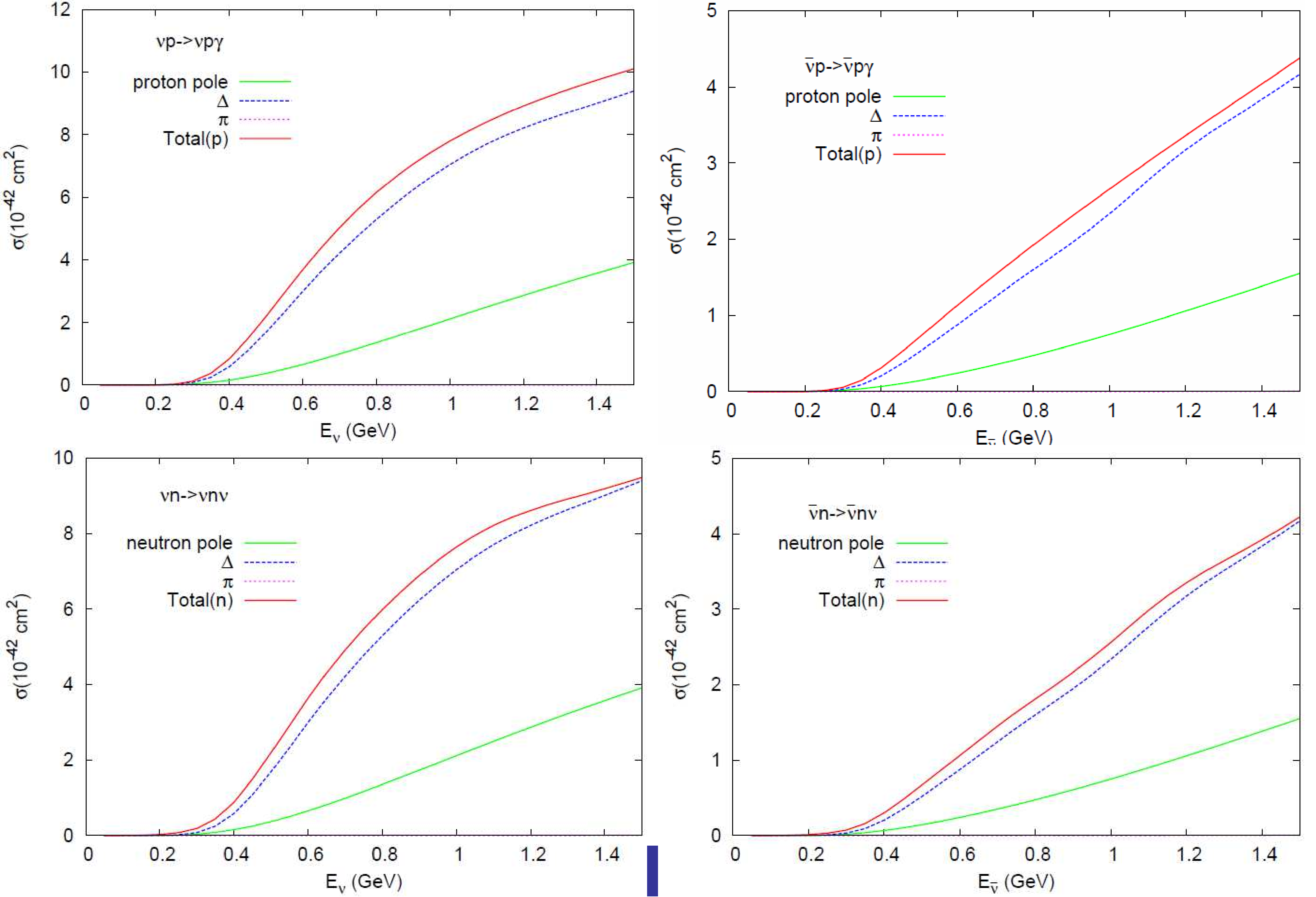
$$\Gamma^{\mu\alpha} = -i c_{p,n} \frac{g_A m_N}{4\pi^2 f_\pi^2} \left(\frac{1}{2} - 2 \sin^2 \theta_W \right) \epsilon^{\sigma\delta\mu\alpha} q_{\gamma\,\sigma} q_\delta \, \gamma_5 D_\pi(p'-p) F_\pi(p'-p)$$

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

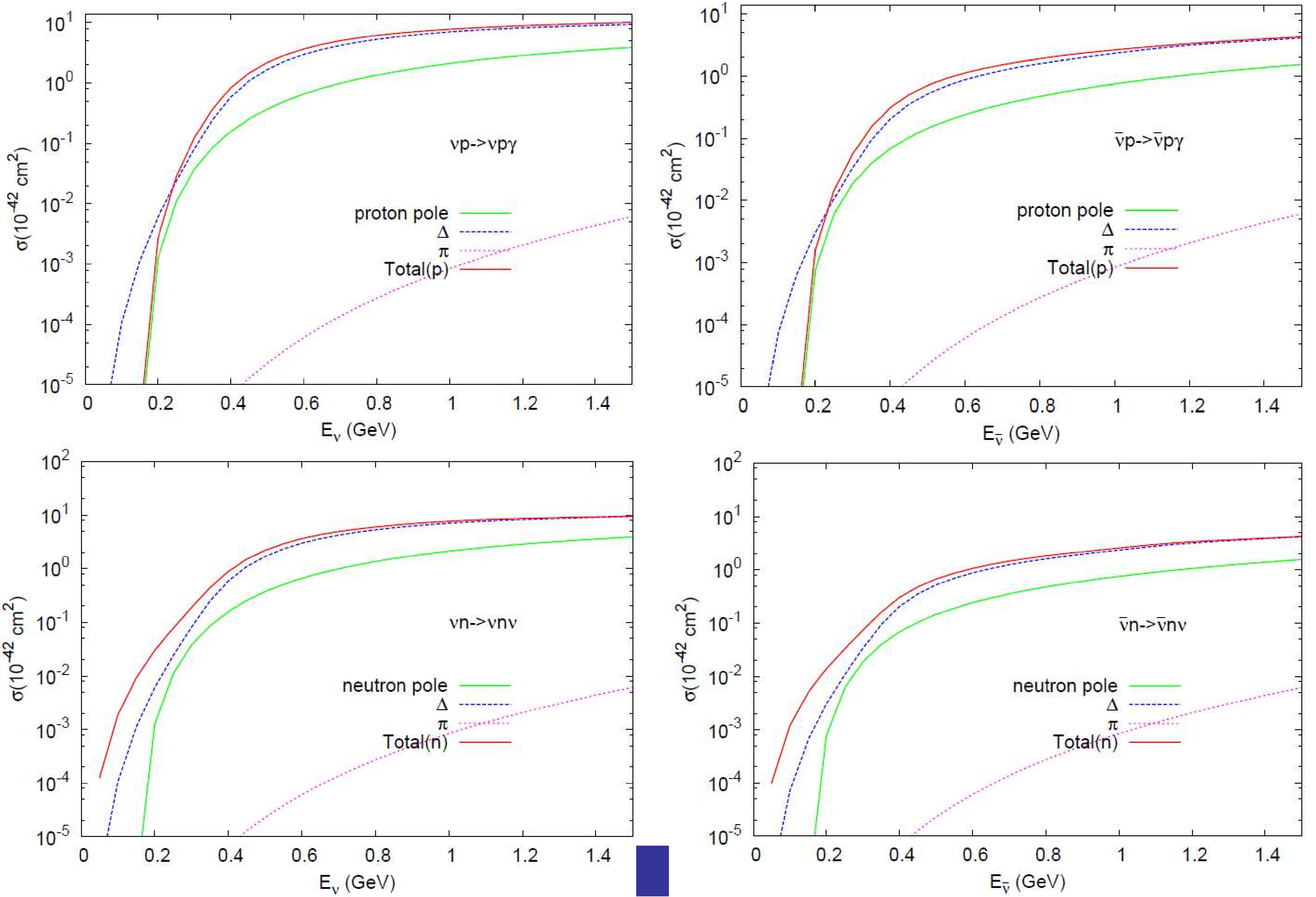
$$F_\pi(p) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - p^2}$$ $\Lambda = 1.2 \text{ GeV}$ $\leftarrow$ off-shell form factor

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

Results

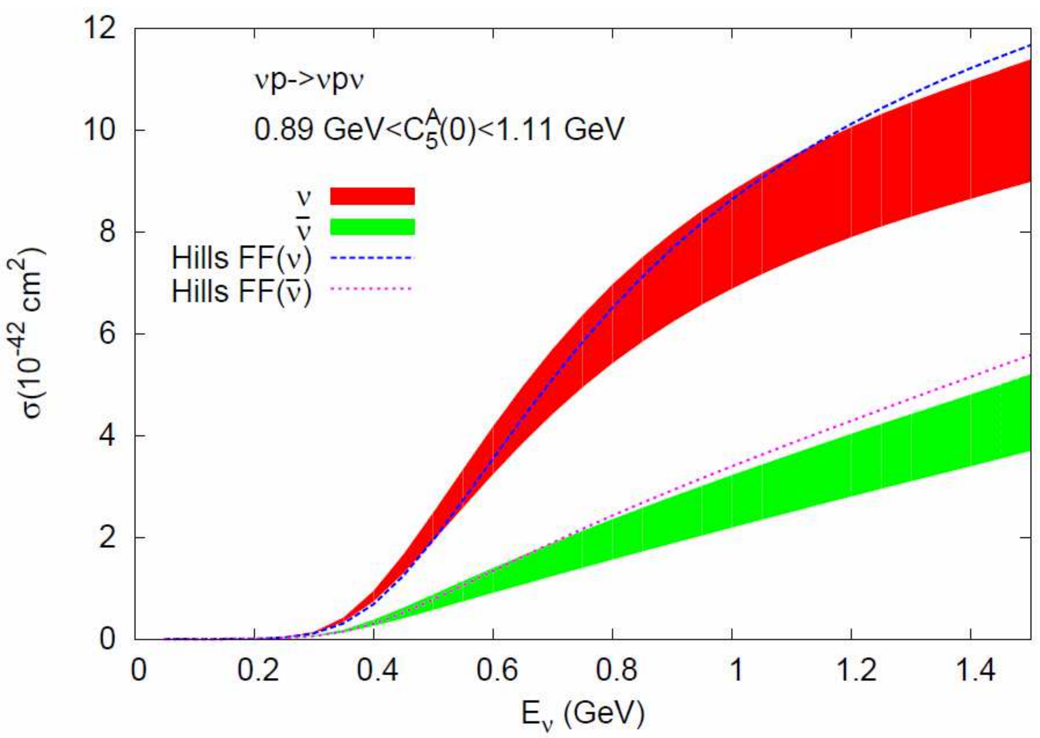

νp->νpγ
proton pole
Δ
π
Total(p)
σ(10^-42 cm^2)
E_ν (GeV)
ν̄p->ν̄pγ
proton pole
Δ
π
Total(p)
σ(10^-42 cm^2)
E_ν̄ (GeV)
νn->νnν
neutron pole
Δ
π
Total(n)
σ(10^-42 cm^2)
E_ν (GeV)
ν̄n->ν̄nν
neutron pole
Δ
π
Total(n)
σ(10^-42 cm^2)
E_ν̄ (GeV)

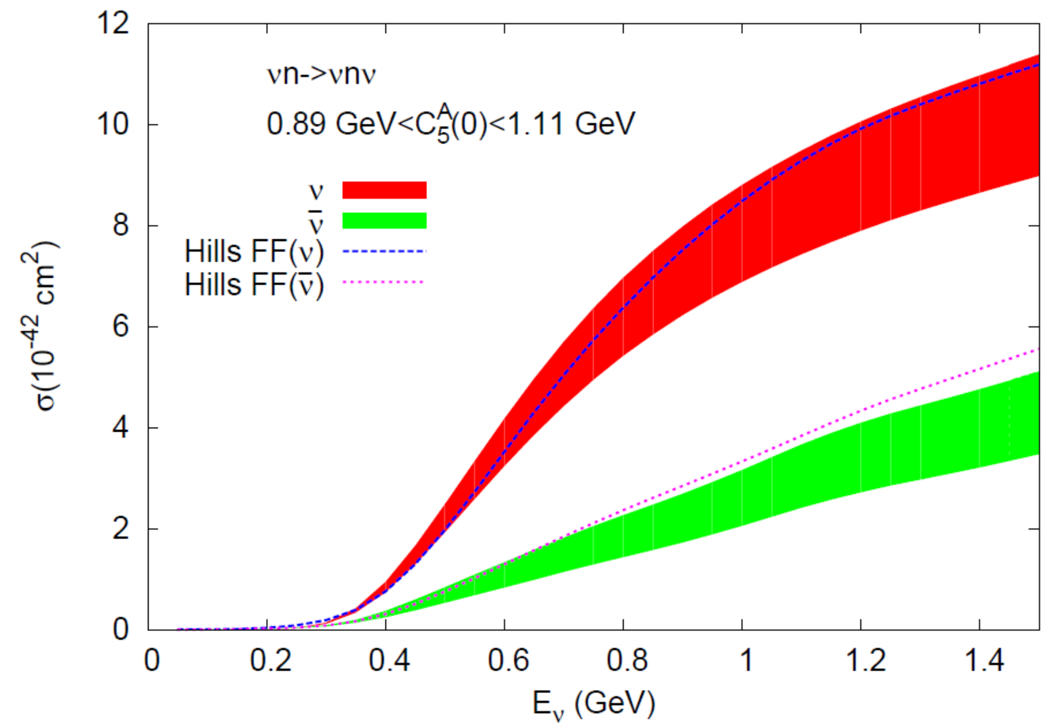
Results



νp->νpγ
proton pole
Δ
π
Total(p)
σ(10^-42 cm^2)
E_ν (GeV)
ν̄p->ν̄pγ
proton pole
Δ
π
Total(p)
σ(10^-42 cm^2)
E_ν̄ (GeV)
νn->νnν
neutron pole
Δ
π
Total(n)
σ(10^-42 cm^2)
E_ν (GeV)
ν̄n->ν̄nν
neutron pole
Δ
π
Total(n)
σ(10^-42 cm^2)
E_ν̄ (GeV)

Results



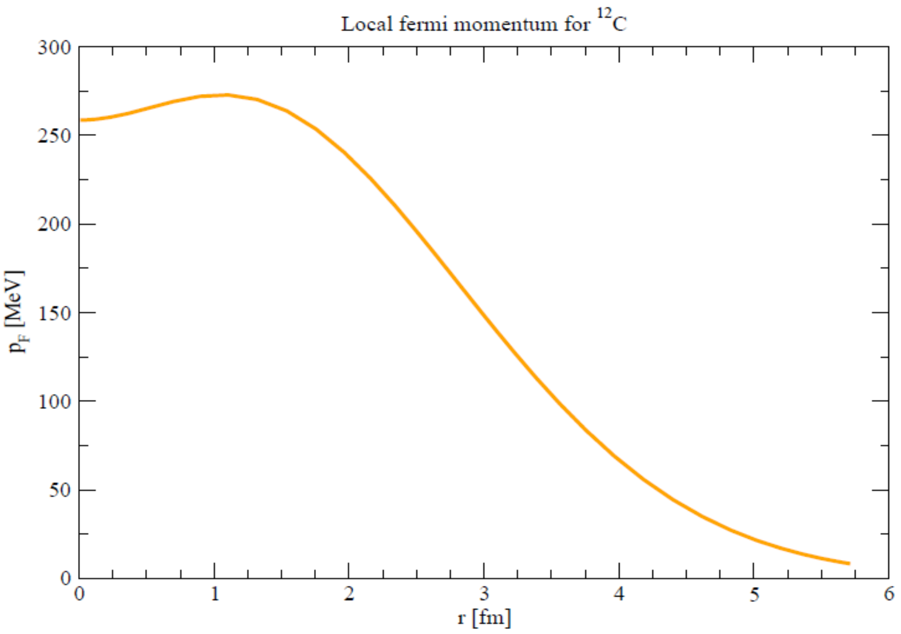


- Error band: $C^A_5(0)$ =1.00 ± 0.11 GeV Hernandez et al., PRD 81 (2010)
- Main differences with R. Hill, PRD 81 (2010)
  - $C^A_5(0)$ = 1.00 ± 0.11 GeV vs 1.2
  - Energy dependent Γ_Δ vs Γ_Δ = const = 120 MeV
  - For nucleon pole diags.: M_A = 1 vs 1.2 GeV

Nuclear effects

- Relativistic Local Fermi Gas

$$p_F(r) = [\tfrac{3}{2}\pi^2\rho(r)]^{1/3}$$



- 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

Nuclear effects

- In-medium modification of the $\Delta(1232)$ resonance

  - In $\dfrac{1}{p^2 - m_\Delta^2 + i m_\Delta \Gamma_\Delta(p^2)}$

replace
$$M_\Delta \rightarrow M_\Delta + \mathrm{Re}\Sigma_\Delta(\rho)$$
$$\frac{\Gamma_\Delta}{2} \rightarrow \frac{\tilde{\Gamma}_\Delta(\rho)}{2} - \mathrm{Im}\Sigma_\Delta(\rho)$$

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

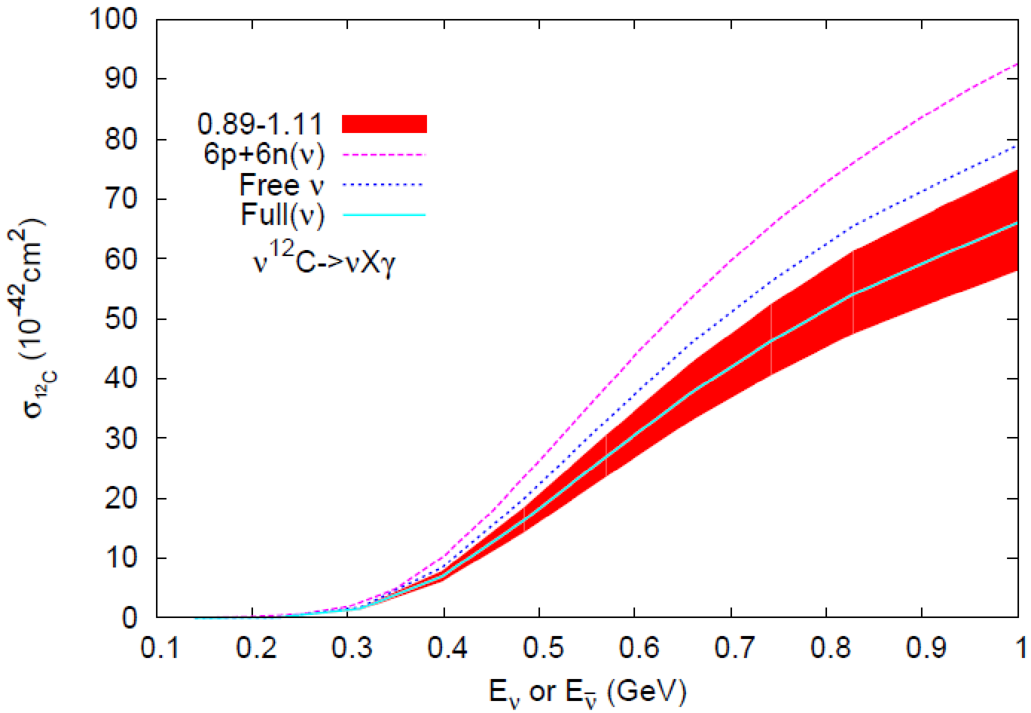
$$\mathrm{Re}\Sigma_\Delta(\rho) \approx 0$$

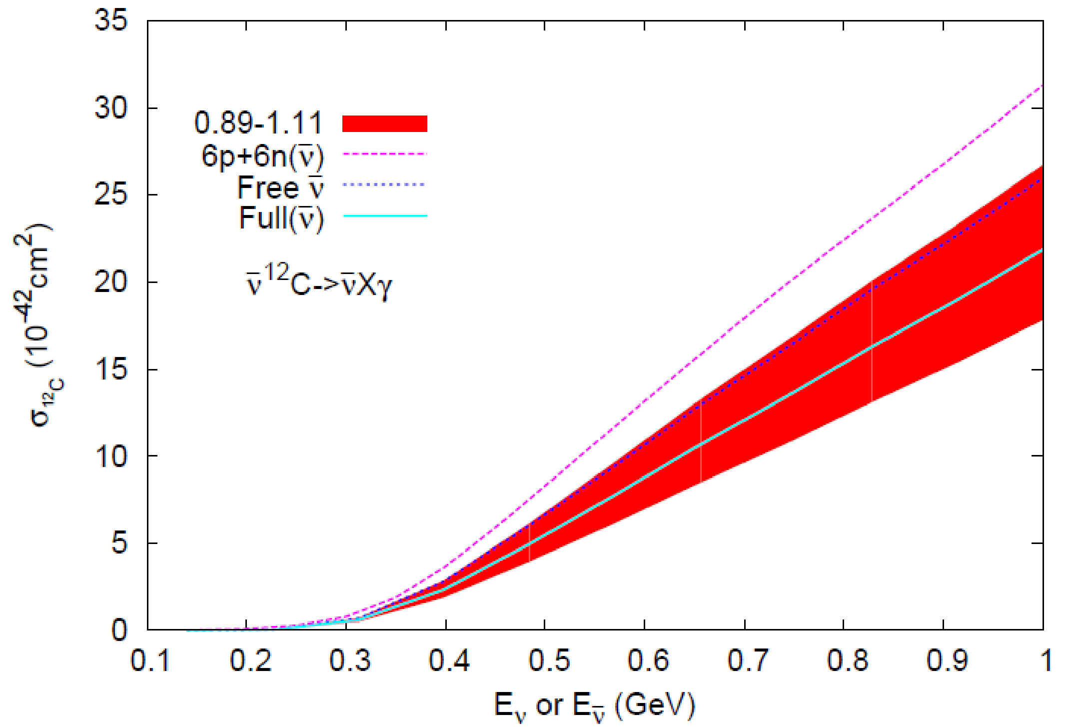
$\mathrm{Im}\Sigma_\Delta(\rho) \leftarrow$ many-body processes:

- $\Delta\, N \rightarrow N\, N$
- $\Delta\, N \rightarrow N\, N\, \pi$
- $\Delta\, N\, N \rightarrow N\, N\, N$

Results

- Integrated cross sections

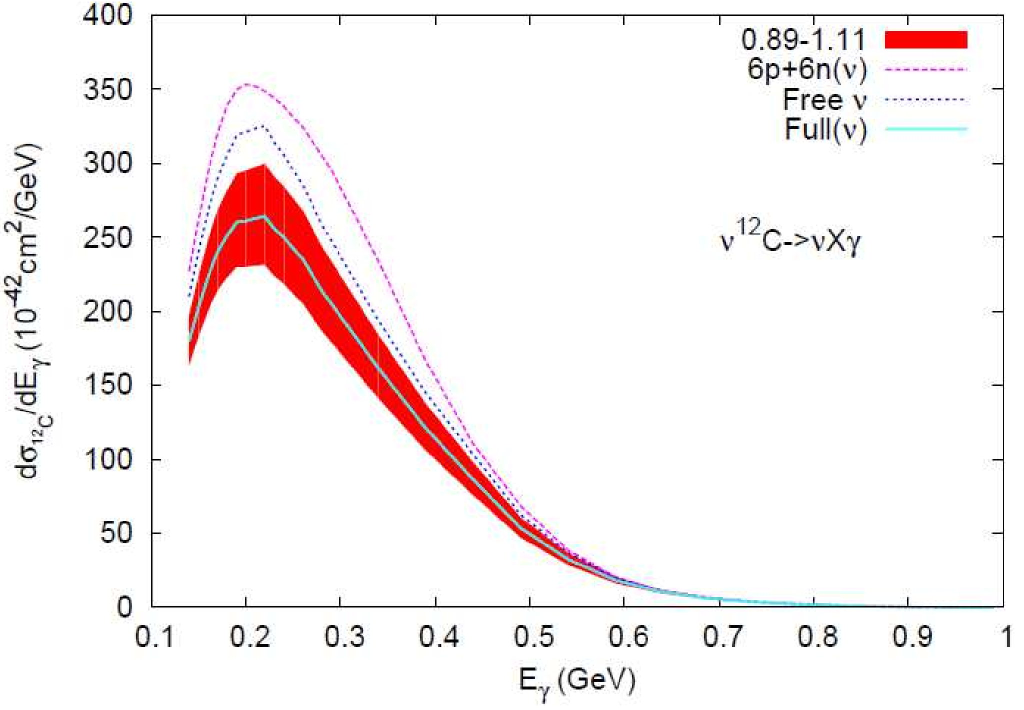


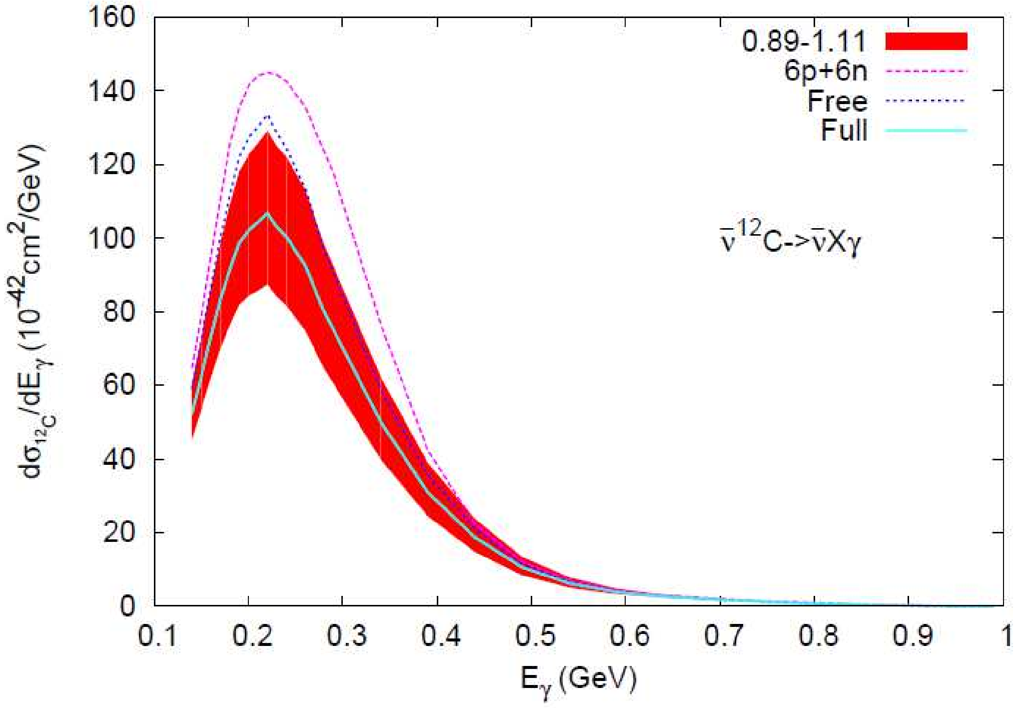


- Considerable reduction caused by nuclear effects (~30 %)
- In line with the results of Zhang, Serot, arXiv:1210.3610

Results

- Photon momentum distributions





- Considerable reduction caused by nuclear effects

ν_e energy reconstruction

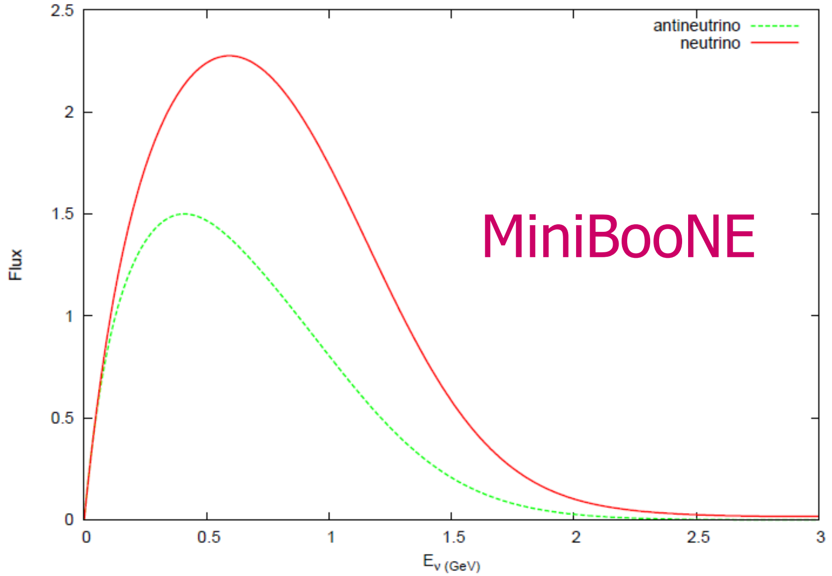
- If the photon from $\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$ is misidentified as a CCQE $e^\pm$ with energy

$$E_\nu^{\rm rec} = \frac{2 m_n E_\gamma - m_e^2 - m_n^2 + m_p^2}{2(m_n - E_\gamma + p_\gamma \cos\theta_\gamma)} \approx \frac{m_N E_\gamma}{m_N - E_\gamma (1 - \cos\theta_\gamma)}$$

- Reconstructed-energy distributions

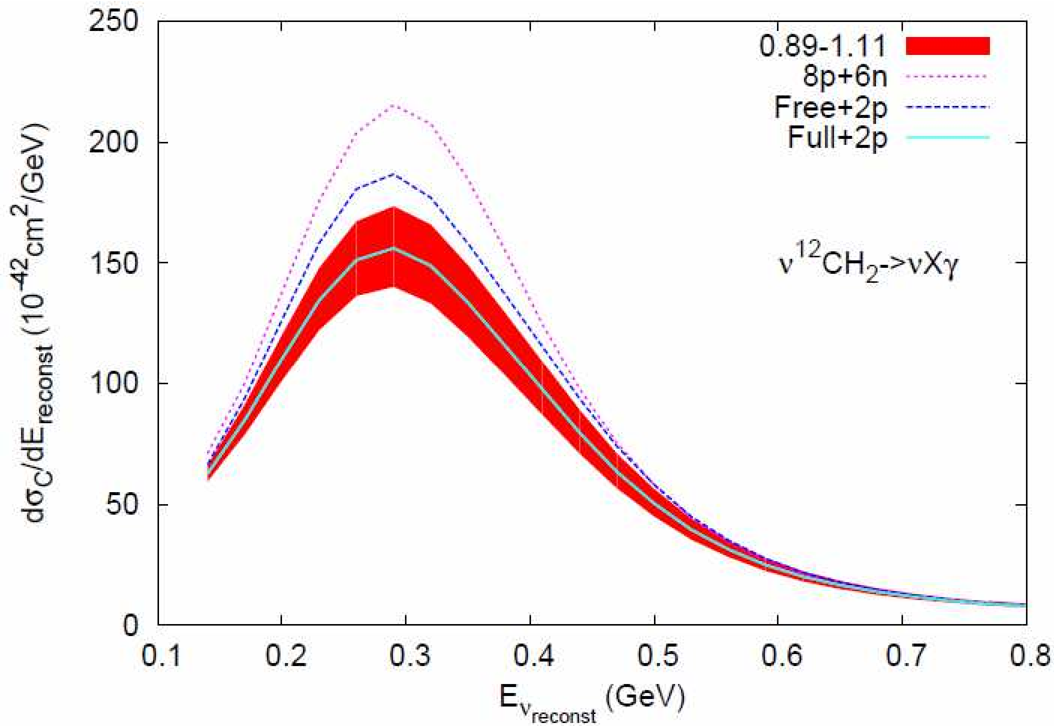
$$\frac{d\sigma}{dE_\nu^{\rm rec}} = \int d\Omega_\gamma dE_\gamma < \frac{d\sigma}{d\Omega_\gamma dE_\gamma} > \delta\left(E_\nu^{\rm rec} - \frac{m_N E_\gamma}{m_N - E_\gamma (1 - \cos\theta_\gamma)} \right)$$

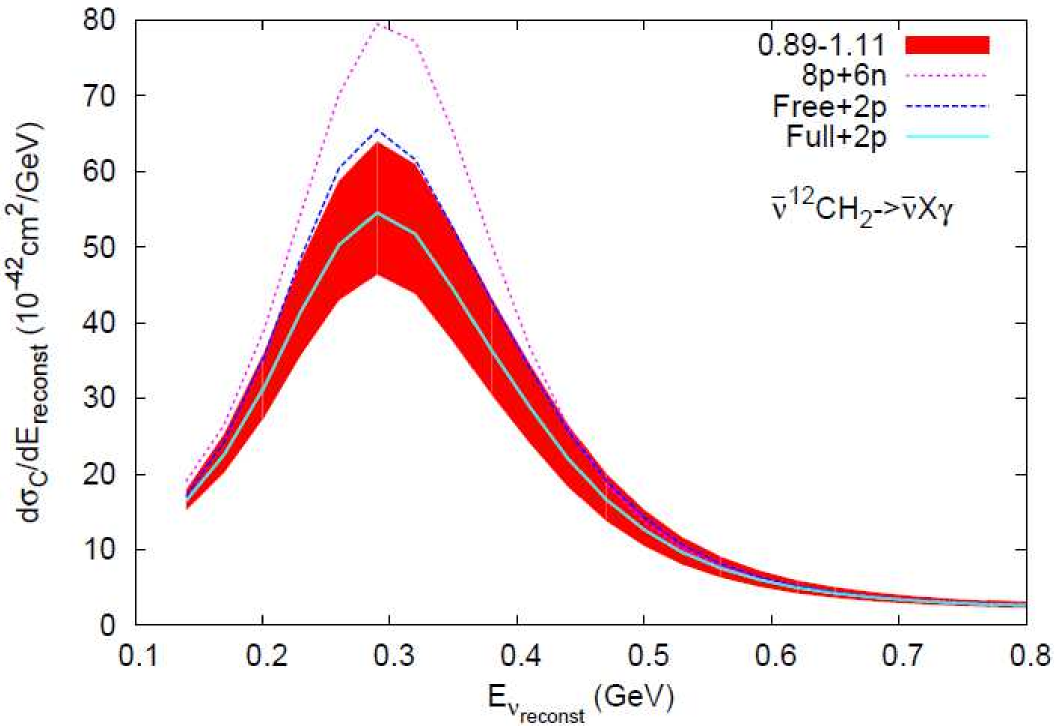
$< \dfrac{d\sigma}{d\Omega_\gamma dE_\gamma} > \leftarrow$ averaged over the ν flux



ν_e energy reconstruction

- Reconstructed-energy distributions



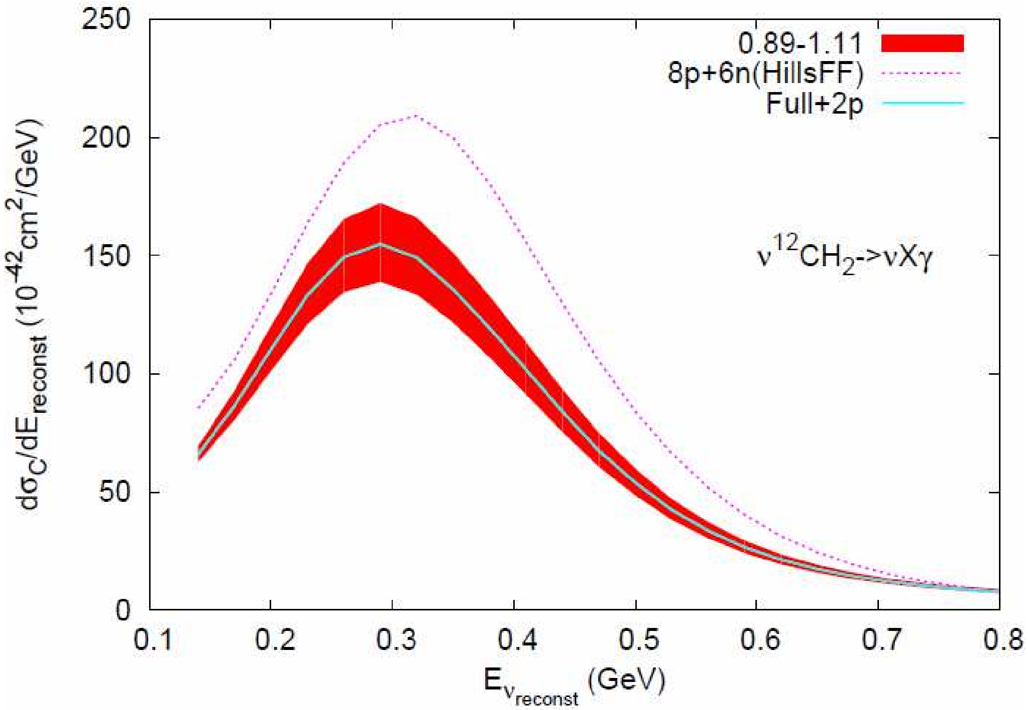


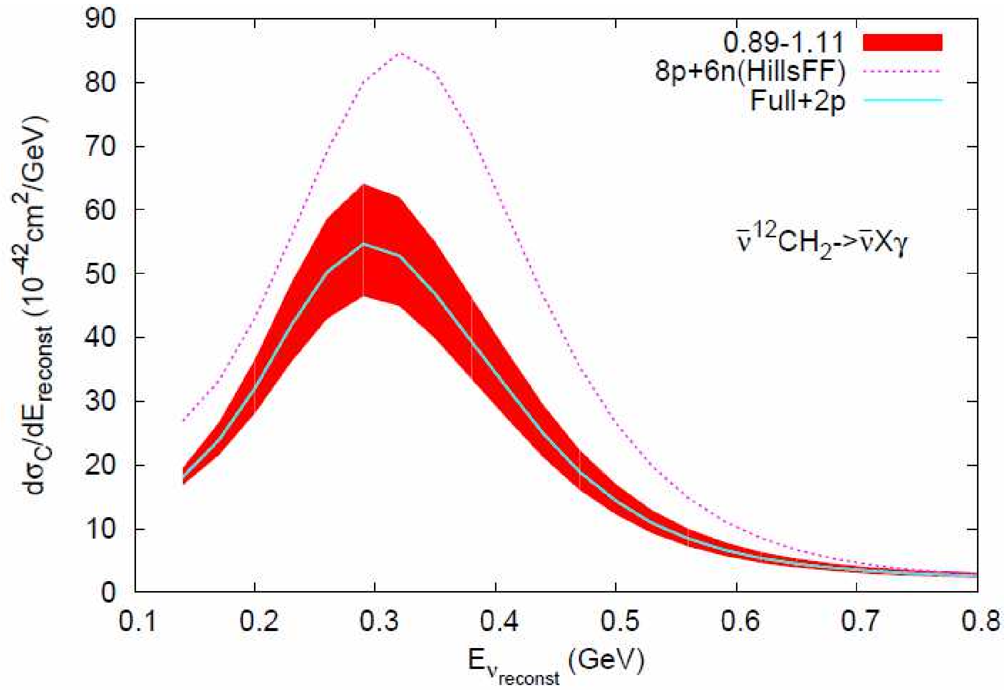
- Peak ~ max of the event excess

  (like in R. Hill, PRD 84 (2011) and Zhang, Serot, arXiv:1210.3610)
- At the peak: ~ 30 % reduction from nuclear effects

ν_e energy reconstruction

- Reconstructed-energy distributions





- Considerably smaller distributions than those that according to R. Hill, PRD 84 (2011) explain the excess of e-like events
- Results probably consistent with MiniBooNE's estimate

Conclusions

- We have studied photon emission induced by NC interactions with nucleons and nuclei in the energy region relevant for the MiniBooNE event excess
- 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
- Smaller peaks in the reconstructed-energy spectra vs R. Hill, PRD 84 (2011)
- Results probably consistent with MiniBooNE's estimate (in line with Zhang, Serot, arXiv:1210.3610) but a direct comparison to e-like events is needed