NC photon production: nuclear models and pion electro- & photo-production

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Brian Serot (Indiana U.)

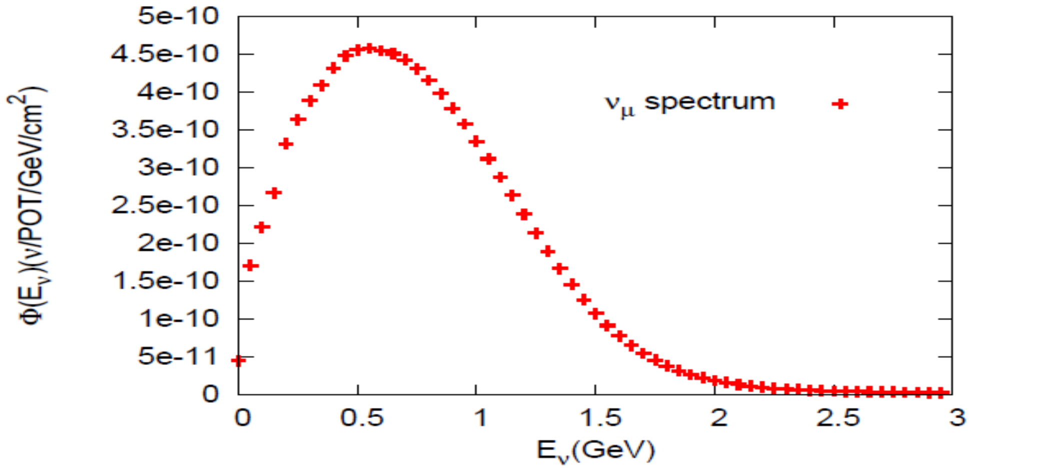
Neutrino-Nucleus Interactions workshop, INT, Seattle, Dec. 2013

Outline

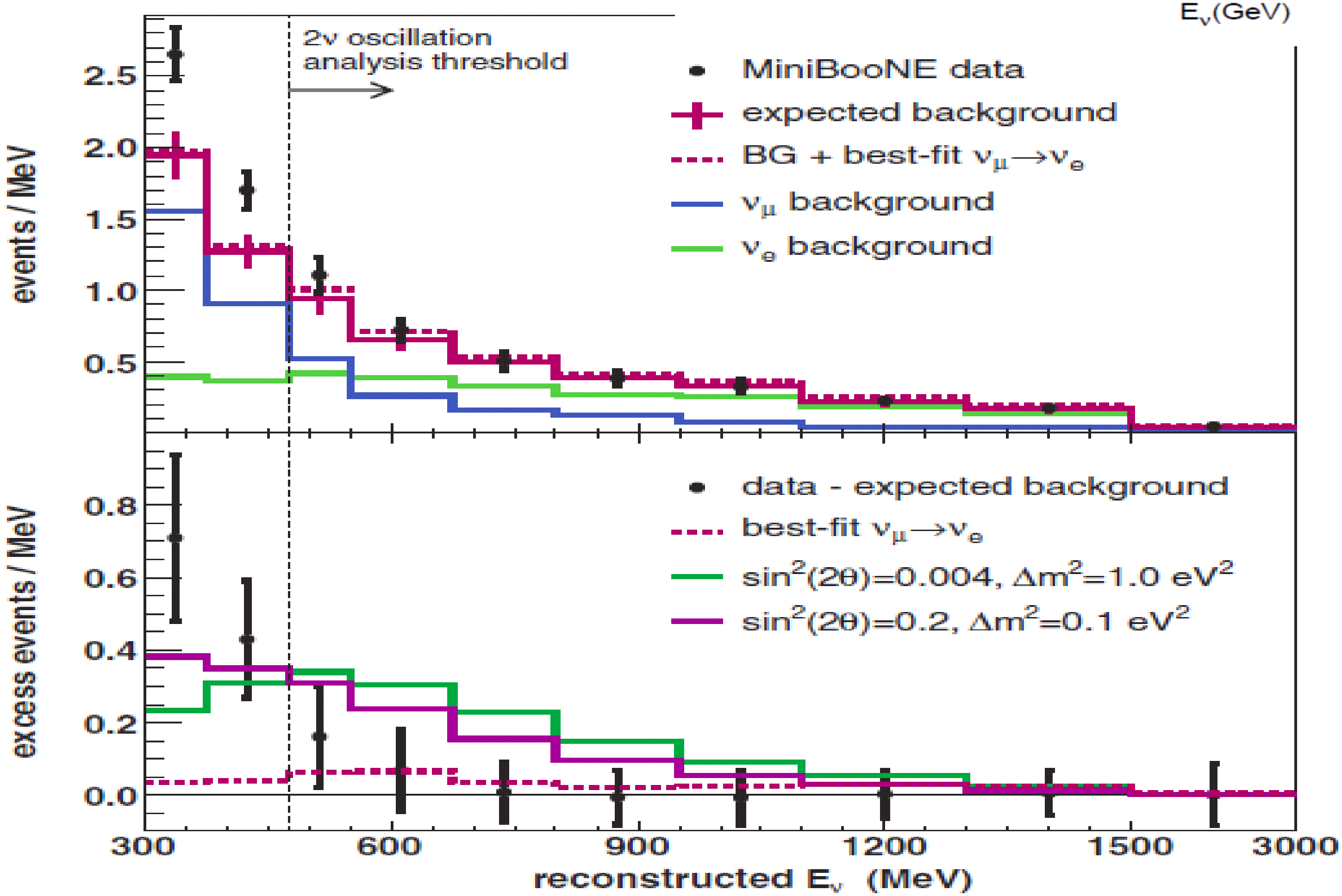
- Motivation: NC photon's role in MiniBooNE low energy excess
- Low energy region: Quantum Hadrondynamics (QHD, or Walecka model)
  - pion and photon production from nucleon
  - incoherent productions: reaction kernel modification in the medium
  - coherent productions
- Extrapolation to GeV region, form factors
- MiniBooNE NC photon production
- Summary & questions

Motivation:
MiniBooNE “low” energy excess

MiniBooNE

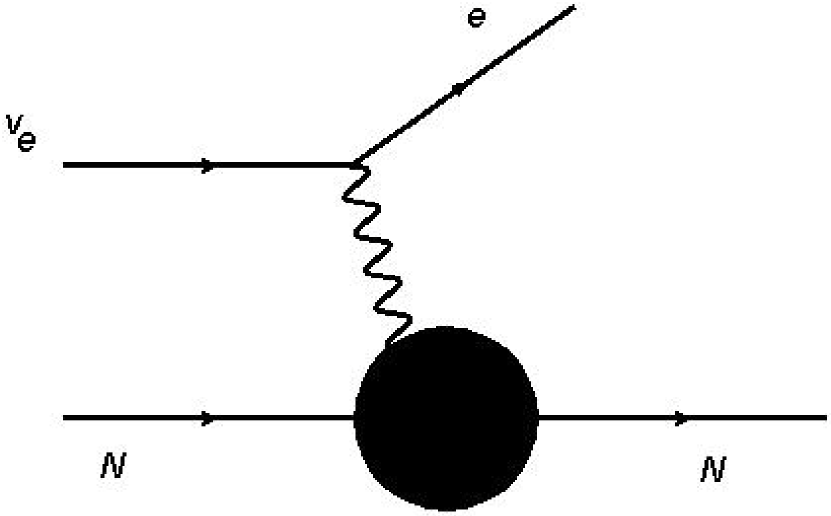


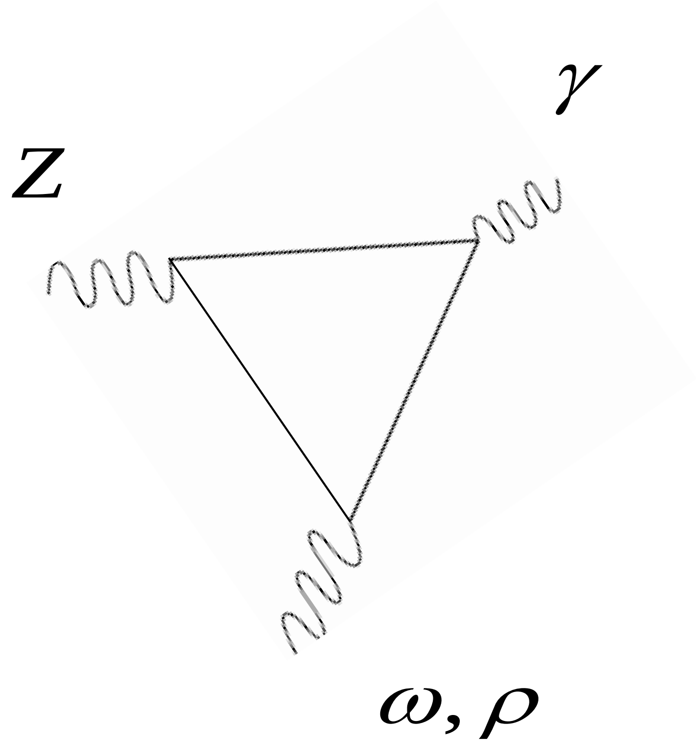
$\Phi(E_\nu)(\nu/POT/GeV/cm^2)$
5e-10
4.5e-10
4e-10
3.5e-10
3e-10
2.5e-10
2e-10
1.5e-10
1e-10
5e-11
0
ν_μ spectrum
0
0.5
1
1.5
2
2.5
3
E_ν(GeV)

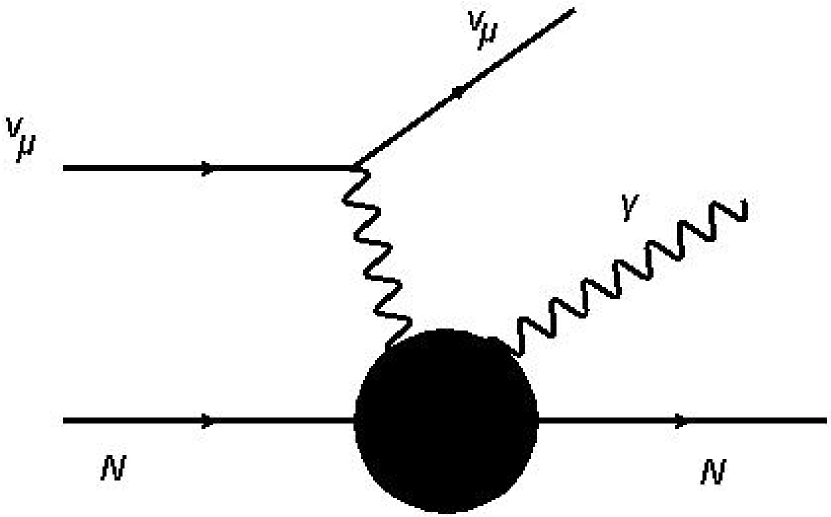


2ν oscillation
analysis threshold
MiniBooNE data
expected background
BG + best-fit $\nu_\mu \to \nu_e$
ν_μ background
ν_e background
events / MeV
2.5
2.0
1.5
1.0
0.5
data - expected background
best-fit $\nu_\mu \to \nu_e$
$\sin^2(2\theta)=0.004$, $\Delta m^2=1.0$ eV^2
$\sin^2(2\theta)=0.2$, $\Delta m^2=0.1$ eV^2
excess events / MeV
0.8
0.6
0.4
0.2
0.0
300
600
900
1200
1500
3000
reconstructed E_ν (MeV)

New hadronic interactions?







J.A. Harvey, C.T. Hill, R.J. Hill, Phys. Rev. Lett. ***99****, 261601 (2007), Phys. Rev. D* ***77****, 085017(2008). R.J. Hill, Phys. Rev. D* ***81,*** *013008 (2010),* ***84*** *017501(2011).*

Production of single photons in the exclusive neutrino process $\nu N \to \nu\gamma N$

S. S. Gershteĭn, Yu. Ya. Komachenko, and M. Yu. Khlopov

Institute of High Energy Physics, Serpukhov
(Submitted 16 January 1981)
Yad. Fiz. 33, 1597–1604 (June 1981)

It is shown that the experimentally observed production of single photons in neutrino interactions involving neutral currents without visible accompaniment of other particles can be explained by the scattering of the neutrino by a virtual ω meson with small momentum transfer to a nucleon and subsequent coherent enhancement of the process in the nucleus.

PACS numbers: 13.15. + g, 14.80.Kx

1. INTRODUCTION

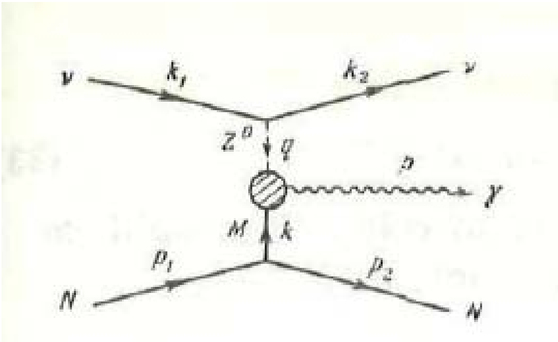
In neutrino experiments performed at CERN using the chamber Gargamelle, more than ten events were detected in which it was observed that single photons with energy 1–10 GeV were produced without visible tracks of any other particles.[1] It can be assumed that the observed events correspond to the weak-electromagnetic process of single-photon production in the reaction

$$\nu N \to \nu\gamma N, \qquad (1)$$

$$H_{\mu\nu} = \sum_M T^{(M)} P^{(M)} J^{(M)}_{\mu\nu}, \qquad (3)$$

in which $T^{(M)}$ is the vertex for emission of a virtual meson (M) by the target nucleon, $P^{(M)}$ is the meson propagator, and $J^{(M)}_{\mu\nu} = \int \langle 0 | T(J^W_\mu(x), J^{EM}_\nu(y)) | M \rangle e^{iqx+ipy} d^4x d^4y$ is the weak-electromagnetic $Z^0 M\gamma$ vertex. The notation for the particle momenta is given in Fig. 2.

In accordance with the estimates of Ref. 3, we shall take into account the contributions to the diagram of Fig.



Proceedings of the DPF-2009 Conference, Detroit, MI, July 27-31, 2009

A phenomenological study of photon production in low energy neutrino nucleon scattering

James Jenkins and T. Goldman
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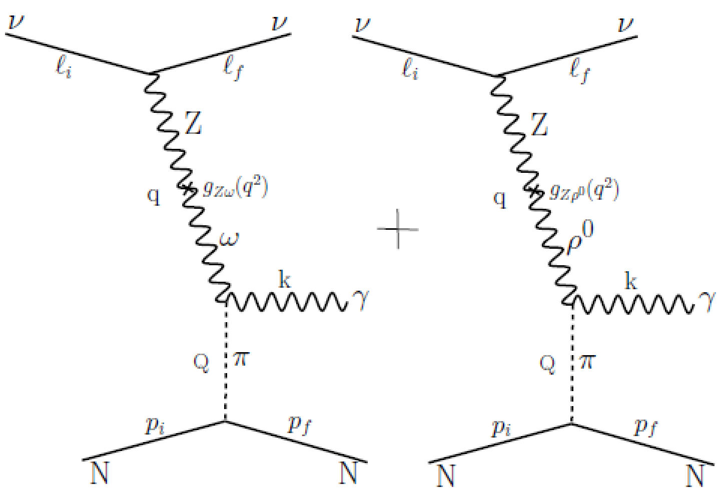
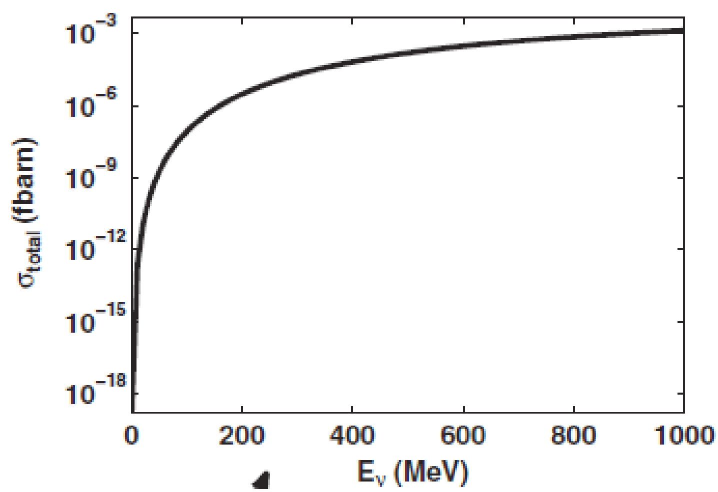
Low energy photon production is an important background to many current and future precision neutrino experiments. We present a phenomenological study of t-channel radiative corrections to neutral current neutrino nucleus scattering. After introducing the relevant processes and phenomenological coupling constants, we will explore the derived energy and angular distributions as well as total cross-section predictions along their estimated uncertainties. This is supplemented throughout with comments on possible experimental signatures and implications. We conclude with a general discussion of the analysis in the context of complimentary methodologies.





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NOMAD exp.

A search for single photon events in neutrino interactions

C.T. Kullenberg [s], S.R. Mishra [s,*], D. Dimmery [s], X.C. Tian [s], D. Autiero [h], S. Gninenko [h,l], A. Rubbia [h,x], S. Alekhin [y], P. Astier [n], A. Baldisseri [r], M. Baldo-Ceolin [m], M. Banner [n], G. Bassompierre [a], K. Benslama [i], N. Besson [r], I. Bird [h,i], B. Blumenfeld [b], F. Bobisut [m], J. Bouchez [r], S. Boyd [t,1], A. Bueno [c,x], S. Bunyatov [f], L. Camilleri [h], A. Cardini [j], P.W. Cattaneo [o], V. Cavasinni [p], A. Cervera-Villanueva [h,v], R. Challis [k],

Letter of Intent: A new investigation of $\nu_\mu \rightarrow \nu_e$ oscillations with improved sensitivity in an enhanced MiniBooNE experiment

MiniBooNE Collaboration

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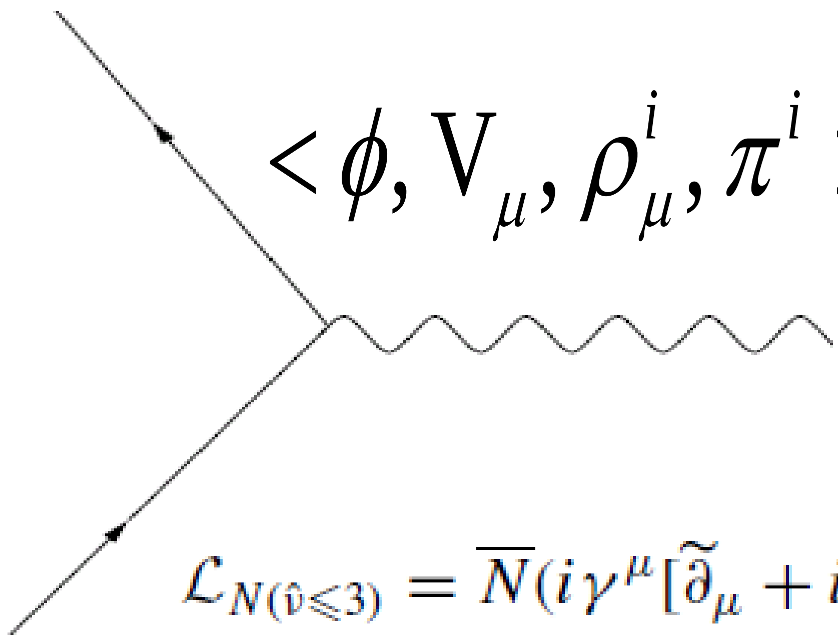
Low energy theory:
Quantum Hadronynamics (QHD)

QHD

- NN interactions (relativistic field theory since 1970):



$$\mathcal{L}_{N(\hat{\nu}\leqslant 3)} = \overline{N}(i\gamma^\mu[\widetilde{\partial}_\mu + ig_\rho\rho_\mu + ig_v V_\mu] + g_A\gamma^\mu\gamma^5\widetilde{a}_\mu - M + g_s\phi)N$$

B. Serot and J. Walecka, Adv. Nucl. Phys. ***16****, 1 (1986)*

QHD

- NN interactions (relativistic field theory since 1970).
- Mean-field approximation (RMF): works for nuclear matter and mid-heavy nuclei; meson fields develop expectation values; nucleon spin-orbital coupling…

$$h_{\mathrm{LS,T}} \doteq \left[\frac{1}{4\overline{M}^2}\frac{1}{r}\left(\frac{d\Phi}{dr}+\frac{dW}{dr}\right)+\frac{f_{\mathrm{v}}}{2M\overline{M}}\frac{1}{r}\frac{dW}{dr}+O(v^4)\right]\boldsymbol{\sigma}\cdot\boldsymbol{L}$$

QHD

- NN interactions (relativistic field theory since 1970).
- Mean-field approximation (RMF): works for nuclear matter and mid-heavy nuclei; meson fields develop expectation values; nucleon spin-orbital coupling…
- Symmetries and currents: Lorentz, EM gauge, Chiral (breaking)→ CVC and PCAC

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_B$$

Y. Hu, J. McIntire, and B. Serot (NPA 794:187, 2007)

QHD

- NN interactions (relativistic field theory since 1970).
- Mean-field approximation (RMF): works for nuclear matter and mid-heavy nuclei; meson fields develop expectation values; nucleon spin-orbital coupling…
- Symmetries and currents.
- Introduce Delta resonance, Delta medium modifications.

$$\mathcal{L}_{\Delta} = \frac{-i}{2} \overline{\Delta}^{a}_{\mu} \{ \sigma^{\mu\nu}, (i \, \widetilde{\not{\partial}} - h_{\rho} \, \not{\rho} - h_{v} \, \not{V} - m + h_{s} \phi) \}^{b}_{a} \Delta_{b\nu}$$

B. Serot and X.Z., Advances in QFT (InTech, 2012) (arXiv:1110.2760)

- Pion dynamics (optical potential)

$$\mathcal{L}_{\Delta,N,\pi} = h_{A} \overline{\Delta}^{a\mu} \, T^{\dagger \, iA}_{a} \, \widetilde{a}_{i\mu} N_{A} + \text{c.c.},$$

Loop calculation: Y. Hu, J. McIntire, and B. Serot NPA 794, 187 (2007)

PHYSICAL REVIEW C **66**, 055502 (2002)

Axial-vector current in nuclear many-body physics

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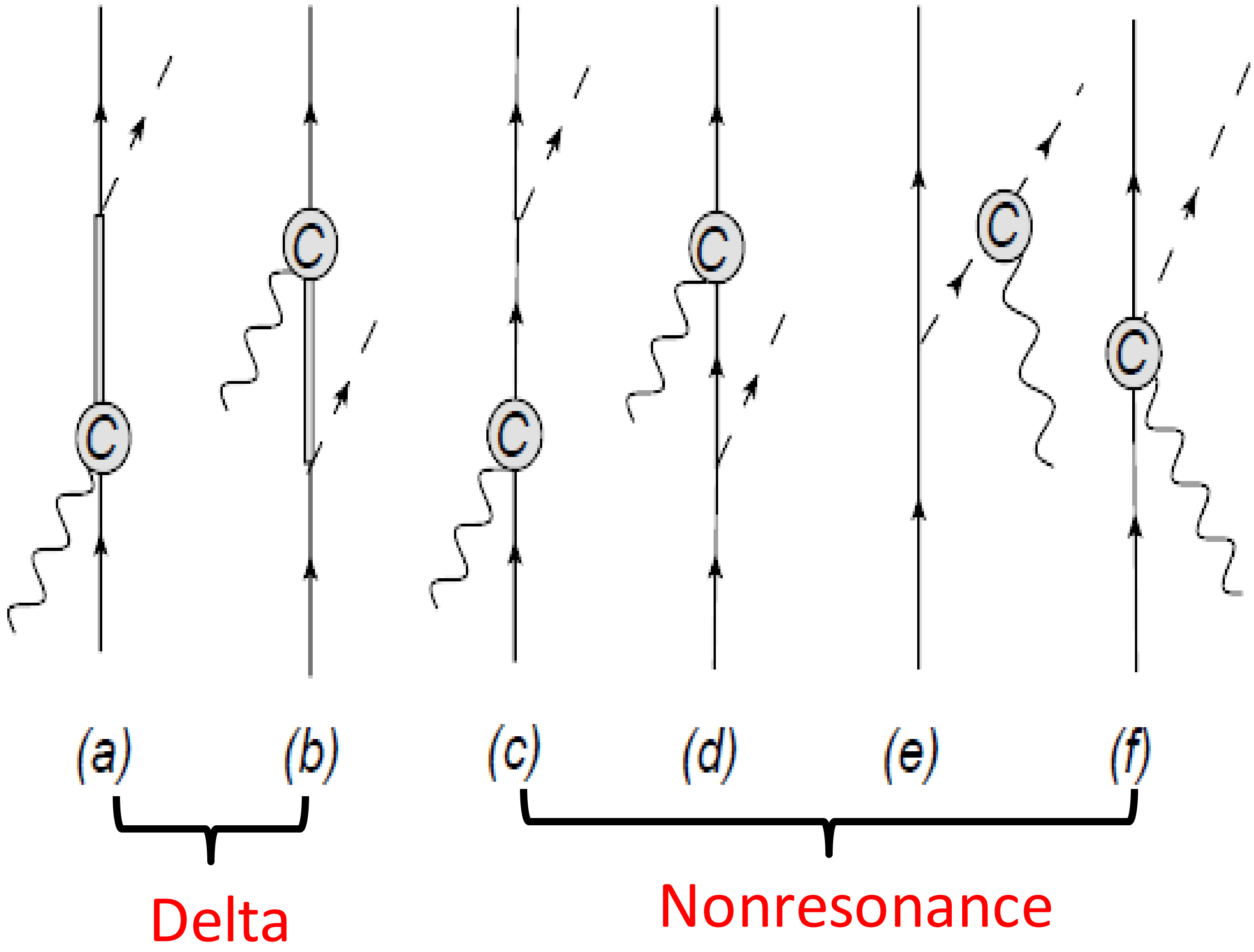
(Received 10 July 2002; published 27 November 2002)

Weak-interaction currents are studied in a recently proposed effective field theory of the nuclear many-body problem. The Lorentz-invariant effective field theory contains nucleons, pions, as well as isoscalar, scalar (σ) and vector (ω) fields, and isovector, vector (ρ) fields. The theory exhibits a nonlinear realization of $SU(2)_L \times SU(2)_R$ chiral symmetry and has three desirable features: it uses the same degrees of freedom to describe the axial-vector current and the strong-interaction dynamics, it satisfies the symmetries of the underlying theory of quantum chromodynamics, and its parameters can be calibrated using strong-interaction phenomena, like hadron scattering or the empirical properties of finite nuclei. Moreover, it has recently been verified that for normal nuclear systems, it is possible to systematically expand the effective Lagrangian in powers of the meson fields (and their derivatives) and to reliably truncate the expansion after the first few orders. Here it is shown that the expressions for the axial-vector current, evaluated through the first few orders in the field expansion, satisfy both PCAC and the Goldberger-Treiman relation, and it is verified that the corresponding vector and axial-vector charges satisfy the familiar chiral charge algebra. Explicit results are derived for the Lorentz-covariant, axial-vector, two-nucleon amplitudes, from which axial-vector meson-exchange currents can be deduced.

Two-body currents

Pion production off the nucleon



B. Serot and X.Z., Phys. Rev. C 86, 015501 (2012) (arXiv:1206.3812)

Nucleon current form factors

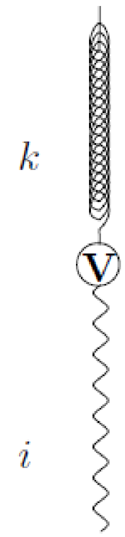
$$\langle N, B|V_\mu^i|N, A\rangle = \langle B|\frac{\tau^i}{2}|A\rangle \overline{u}_f \left(\gamma_\mu + 2\delta F_1^{V,md}\frac{q^2\gamma_\mu - \not{q}q_\mu}{q^2} + 2F_2^{V,md}\frac{\sigma_{\mu\nu}iq^\nu}{2M}\right)u_i$$

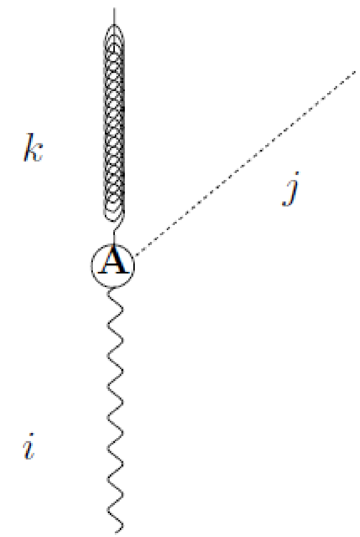
$$F_1^{V,md} = \frac{1}{2}\left(1 + \frac{\beta^{(1)}}{M^2}q^2 - \frac{g_\rho}{g_\gamma}\frac{q^2}{q^2 - m_\rho^2}\right)$$

Meson Dominance:

$$\frac{1}{2g_\gamma}\left(\mathrm{Tr}(F^{(+)\mu\nu}\rho_{\mu\nu}) + \tfrac{1}{3} f_s^{\mu\nu} V_{\mu\nu}\right)$$

$$F_{\mu\nu}^{(+)} \approx 2\partial_{[\mu}\mathrm{v}_{\nu]} + 2\epsilon^{ijk}\frac{\pi_j}{f_\pi}\frac{\tau_k}{2}\partial_{[\mu}\mathrm{a}_{i\nu]}$$





Nucleon current form factors

$$\langle N,B|V_\mu^i|N,A\rangle = \langle B|\frac{\tau^i}{2}|A\rangle \overline{u}_f \left(\gamma_\mu + 2\delta F_1^{V,md}\frac{q^2\gamma_\mu - \not{q}q_\mu}{q^2} + 2F_2^{V,md}\frac{\sigma_{\mu\nu}iq^\nu}{2M}\right)u_i$$

$$\langle N,B;\pi,j,k_\pi|A_\mu^i|N,A\rangle = -\frac{\epsilon^i{}_{jk}}{f_\pi}\langle B|\frac{\tau^k}{2}|A\rangle \overline{u}_f\gamma^\nu u_i\left[g_{\mu\nu} + 2\delta F_1^{V,md}((q-k_\pi)^2)\frac{q\cdot(q-k_\pi)g_{\mu\nu} - (q-k_\pi)_\mu q_\nu}{(q-k_\pi)^2}\right]$$

$$-\frac{\epsilon^i{}_{jk}}{f_\pi}\langle B|\frac{\tau^k}{2}|A\rangle \overline{u}_f\frac{\sigma_{\mu\nu}iq^\nu}{2M}u_i\left[2\lambda^{(1)} + 2\delta F_2^{V,md}((q-k_\pi)^2)\frac{q\cdot(q-k_\pi)}{(q-k_\pi)^2}\right]$$

Meson Dominance. This will be used in high energy extrapolation.

$$\langle N,B|A_\mu^i|N,A\rangle = -G_A^{md}(q^2)\langle B|\frac{\tau^i}{2}|A\rangle \overline{u}_f\left(\gamma_\mu - \frac{q_\mu \not{q}}{q^2 - m_\pi^2}\right)\gamma^5 u_i \quad ?$$

$$G_A(q^2) = g_A/(1-q^2/M_A^2)^2 \quad ?$$

T. Ericson and W. Weise, *Pions and Nuclei (Clarendon, Oxford,*1988).

Transition form factors

$$\langle \Delta, a, p_\Delta | V^{i\mu}(A^{i\mu}) | N, A, p_N \rangle \equiv T_a^{\dagger iA}\, \overline{u}_{\Delta\alpha}(p_\Delta)\, \Gamma^{\alpha\mu}_{V(A)}(q)\, u_N(p_N)$$

$$\Gamma_V^{\alpha\mu} = \frac{2c_{1\Delta}(q^2)}{M}(q^\alpha \gamma^\mu - \not{q} g^{\alpha\mu})\gamma^5 + \frac{2c_{3\Delta}(q^2)}{M^2}(q^\alpha q^\mu - g^{\alpha\mu} q^2)\gamma^5 - \frac{8c_{6\Delta}(q^2)}{M^2} q^\alpha \sigma^{\mu\nu} i q_\nu \gamma^5,$$

$$\Gamma_A^{\alpha\mu} = -h_A\left(g^{\alpha\mu} - \frac{q^\alpha q^\mu}{q^2 - m_\pi^2}\right) + \frac{2d_{2\Delta}}{M^2}(q^\alpha q^\mu - g^{\alpha\mu} q^2) - \frac{2d_{4\Delta}}{M}(q^\alpha \gamma^\mu - g^{\alpha\mu} \not{q}) - \frac{4d_{7\Delta}}{M^2} q^\alpha \sigma^{\mu\nu} i q_\nu$$

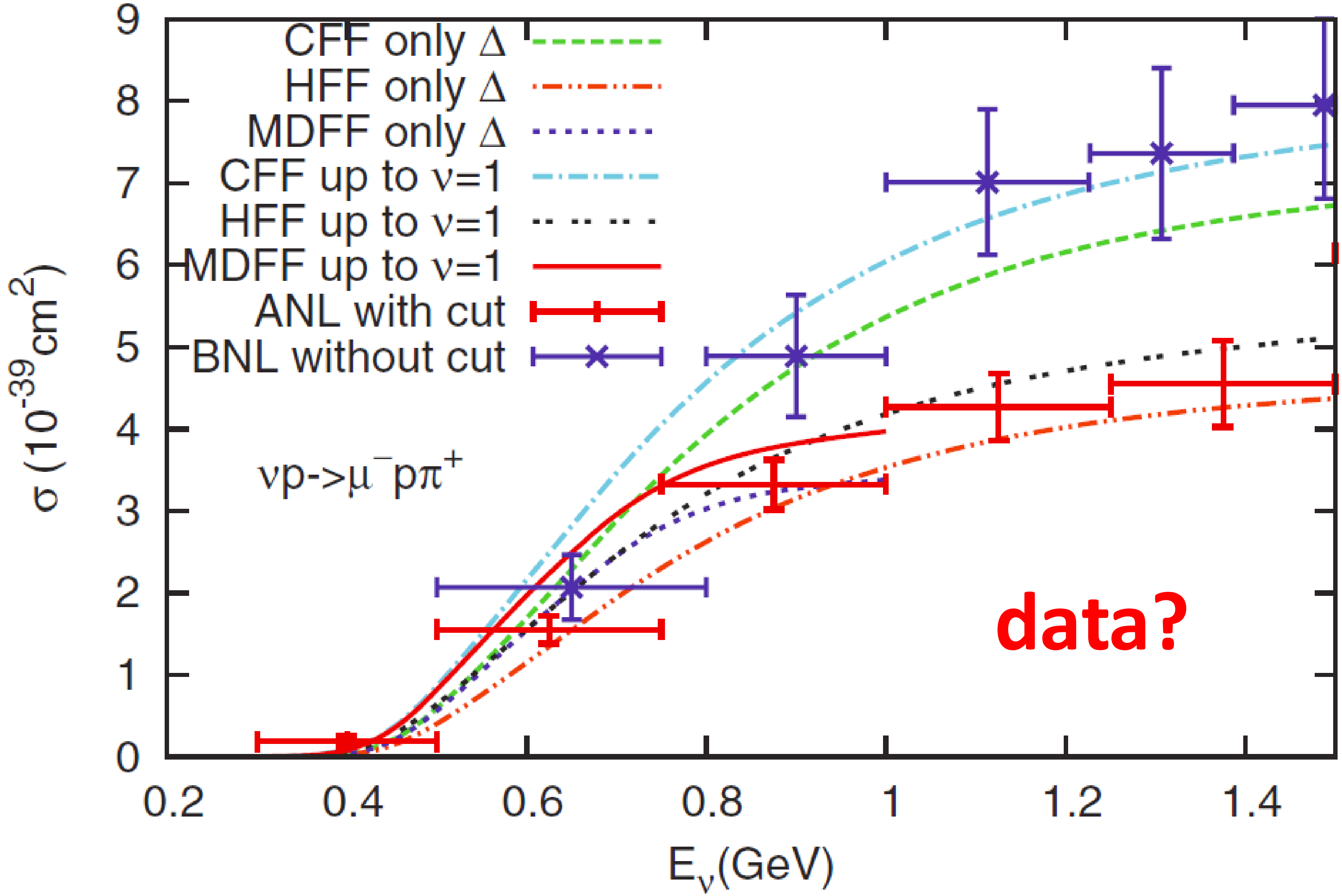
$$h_A(q^2) \equiv h_A + h_{\Delta a_1}\frac{q^2}{q^2 - m_{a_1}^2}, \quad d_{i\Delta}(q^2) \equiv d_{i\Delta} + d_{i\Delta a_1}\frac{q^2}{q^2 - m_{a_1}^2}$$

Meson dominance FF (MDFF)

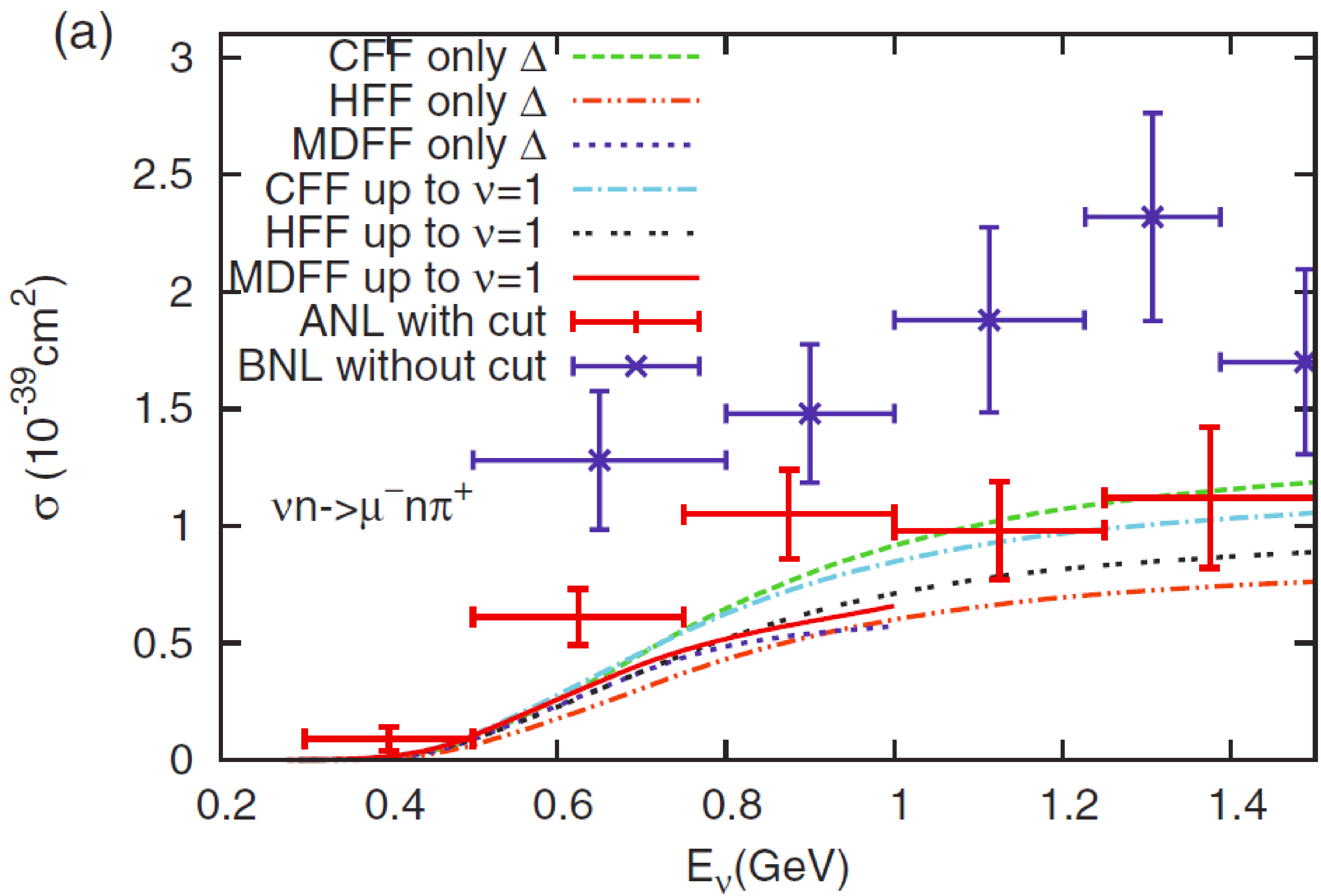
$$\overline{u}_\alpha(p_\Delta)\left\{\left[\frac{C_3^V}{M}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^V}{M^2}(q\cdot p_\Delta\, g^{\alpha\mu} - q^\alpha p_\Delta^\mu) + \frac{C_5^V}{M^2}(q\cdot p_N\, g^{\alpha\mu} - q^\alpha p_N^\mu)\right]\gamma^5 + \left[\frac{C_3^A}{M}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^A}{M^2}(q\cdot p_\Delta\, g^{\alpha\mu} - q^\alpha p_\Delta^\mu) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M^2} q^\mu q^\alpha\right]\right\} u(p_N).$$

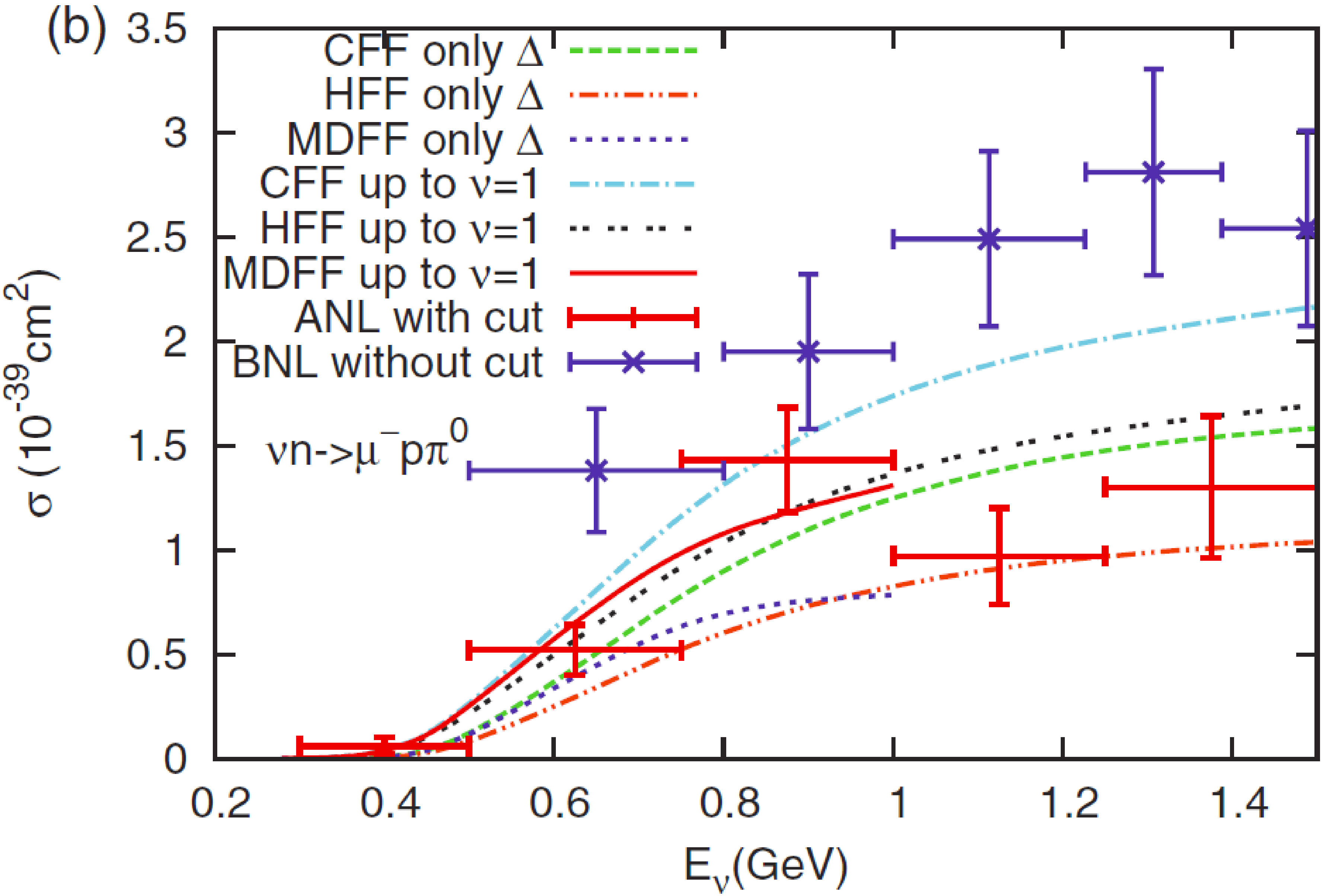
?

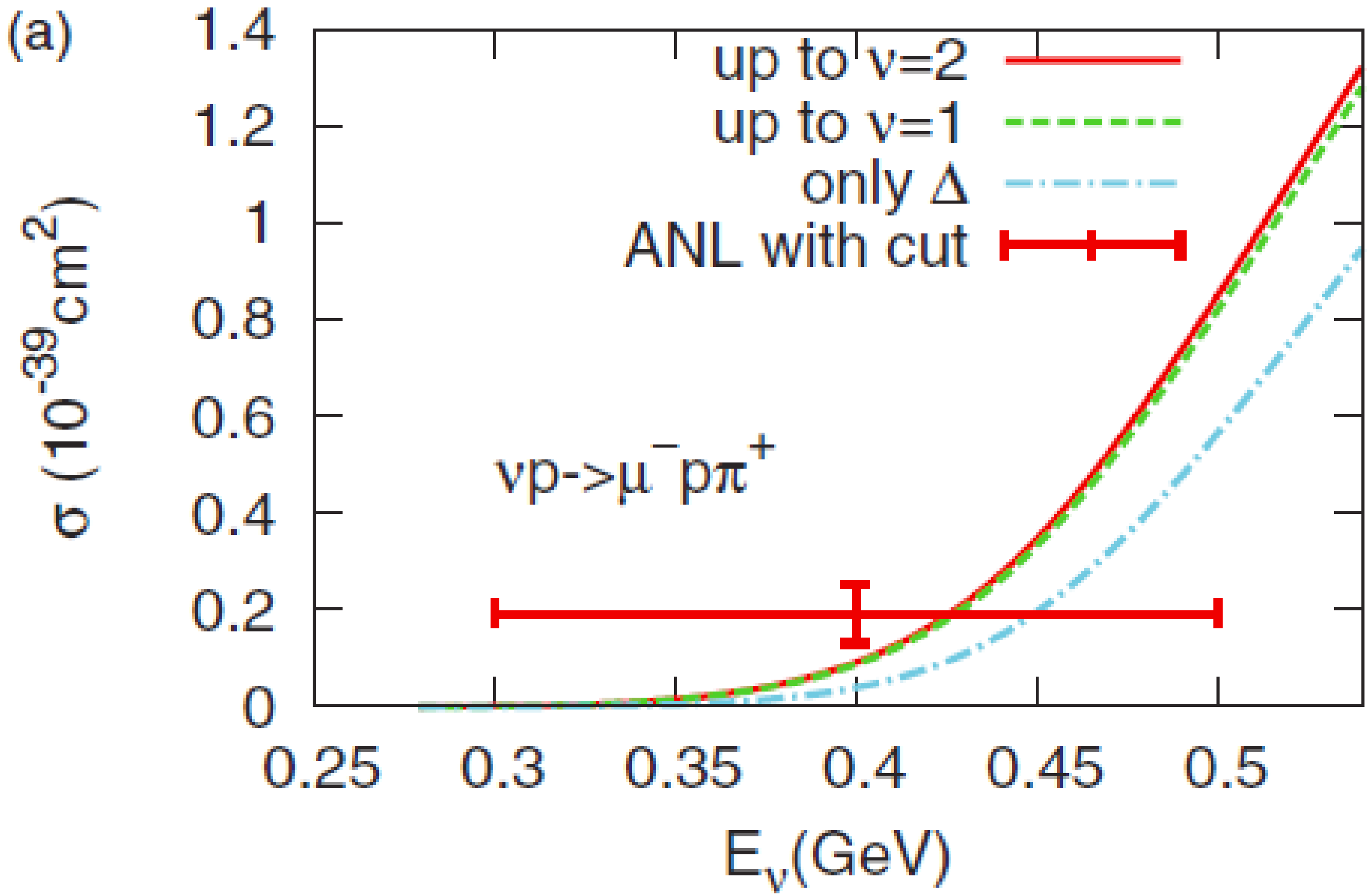
*K. Graczyk, D. Kiełczewska, P. Przewłocki, and J. Sobczyk, PRD **80**, 093001 (2009). (CFF)*
*E. Hern´andez, J. Nieves, and M. Valverde, PRD **76**, 033005 (2007). (HFF with C5a reduced)*



K. Graczyk, D. Kiełczewska, P. Przewłocki, and J. Sobczyk, PRD ***80****, 093001 (2009).*
E. Hern´andez, J. Nieves, and M. Valverde, PRD ***76****, 033005 (2007).*
G. M. Radecky et al., PRD ***25****, 1161 (1982); T. Kitagaki et al., PRD* ***34****, 2554 (1986).*

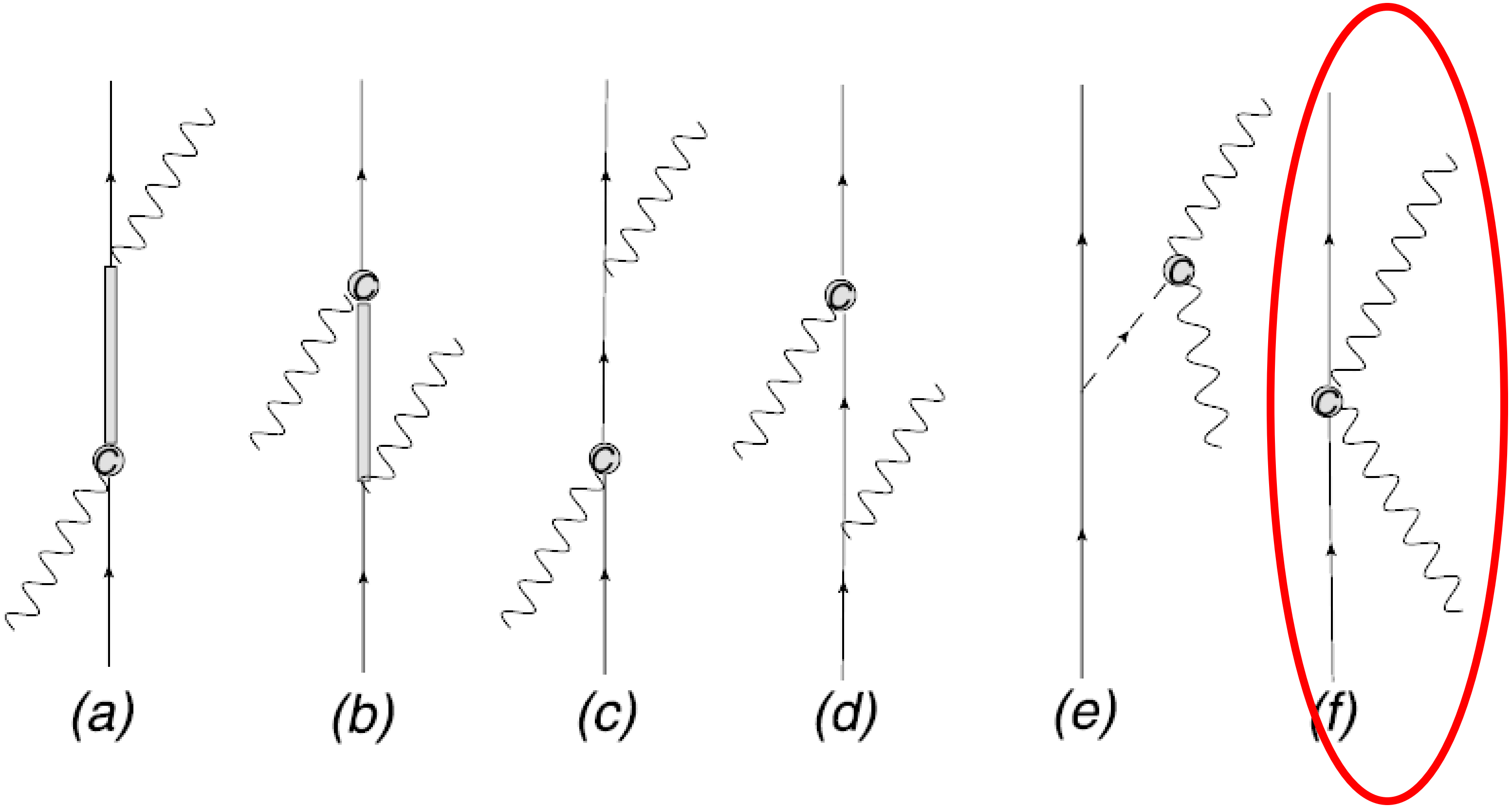

(a)
CFF only Δ
HFF only Δ
MDFF only Δ
CFF up to ν=1
HFF up to ν=1
MDFF up to ν=1
ANL with cut
BNL without cut
νn->μ⁻nπ⁺
σ (10⁻³⁹cm²)
E_ν(GeV)
0
0.5
1
1.5
2
2.5
3
0.2
0.4
0.6
0.8
1
1.2
1.4

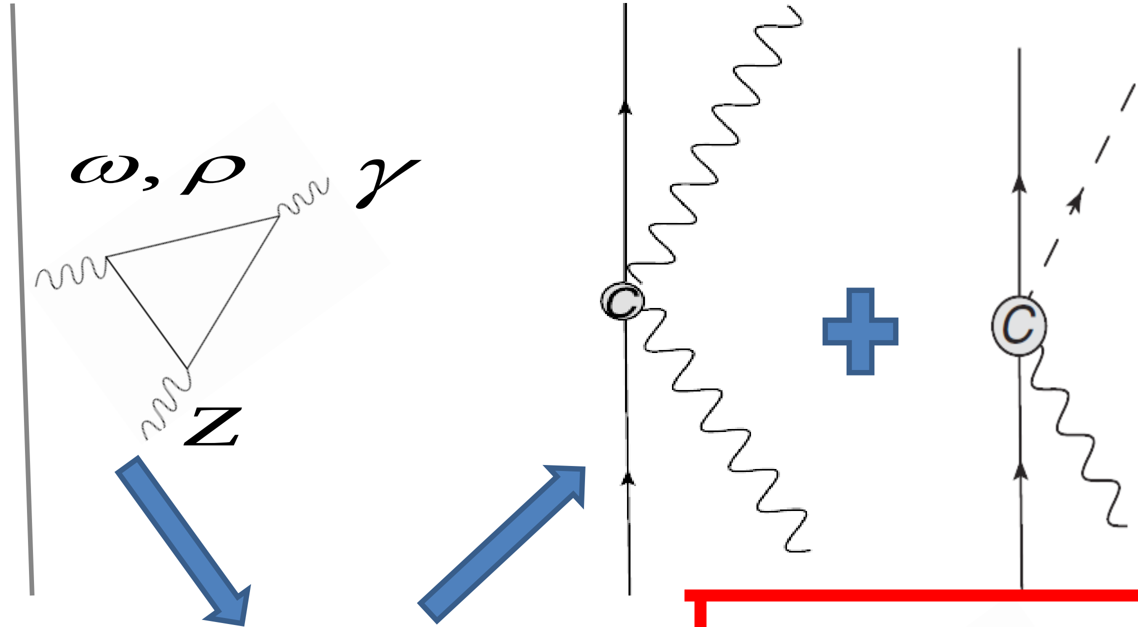

(b)
CFF only Δ
HFF only Δ
MDFF only Δ
CFF up to ν=1
HFF up to ν=1
MDFF up to ν=1
ANL with cut
BNL without cut
νn->μ⁻pπ⁰
σ (10⁻³⁹cm²)
Eν(GeV)
0
0.5
1
1.5
2
2.5
3
3.5
0.2
0.4
0.6
0.8
1
1.2
1.4



Power counting of the calculation

NC photon production off the nucleon



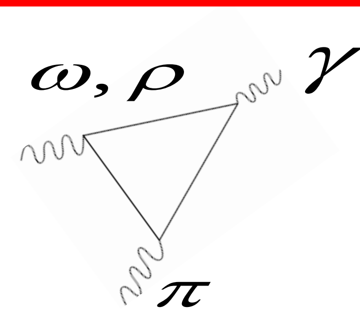


$$\frac{c_1}{M^2}\overline{N}\gamma^\mu N\,\mathrm{Tr}(\tilde{a}^\nu \overline{F}^{(+)}_{\mu\nu}), \qquad \frac{e_1}{M^2}\overline{N}\gamma^\mu \tilde{a}^\nu N \overline{f}_{s\mu\nu}$$

$$F^{(+)}_{\mu\nu} \approx 2\partial_{[\mu}\mathrm{v}_{\nu]} + 2\epsilon^{ijk}\frac{\pi_j}{f_\pi}\frac{\tau_k}{2}\partial_{[\mu}\mathrm{a}_{i\nu]}$$

$$\tilde{a}_\mu \approx \frac{1}{f_\pi}\partial_\mu \pi^i \frac{\tau_i}{2} + \mathrm{a}_{i\mu}\frac{\tau^i}{2} + \epsilon^{ijk}\frac{\pi_j}{f_\pi}\frac{\tau_k}{2}\mathrm{v}_{i\mu}$$

*R. J. Hill, Phys. Rev. D **81**, 013008 (2010)*
W. Peters l, H. Lenske, U. Mosel,
Nucl. Phy. A640,89 (1998)



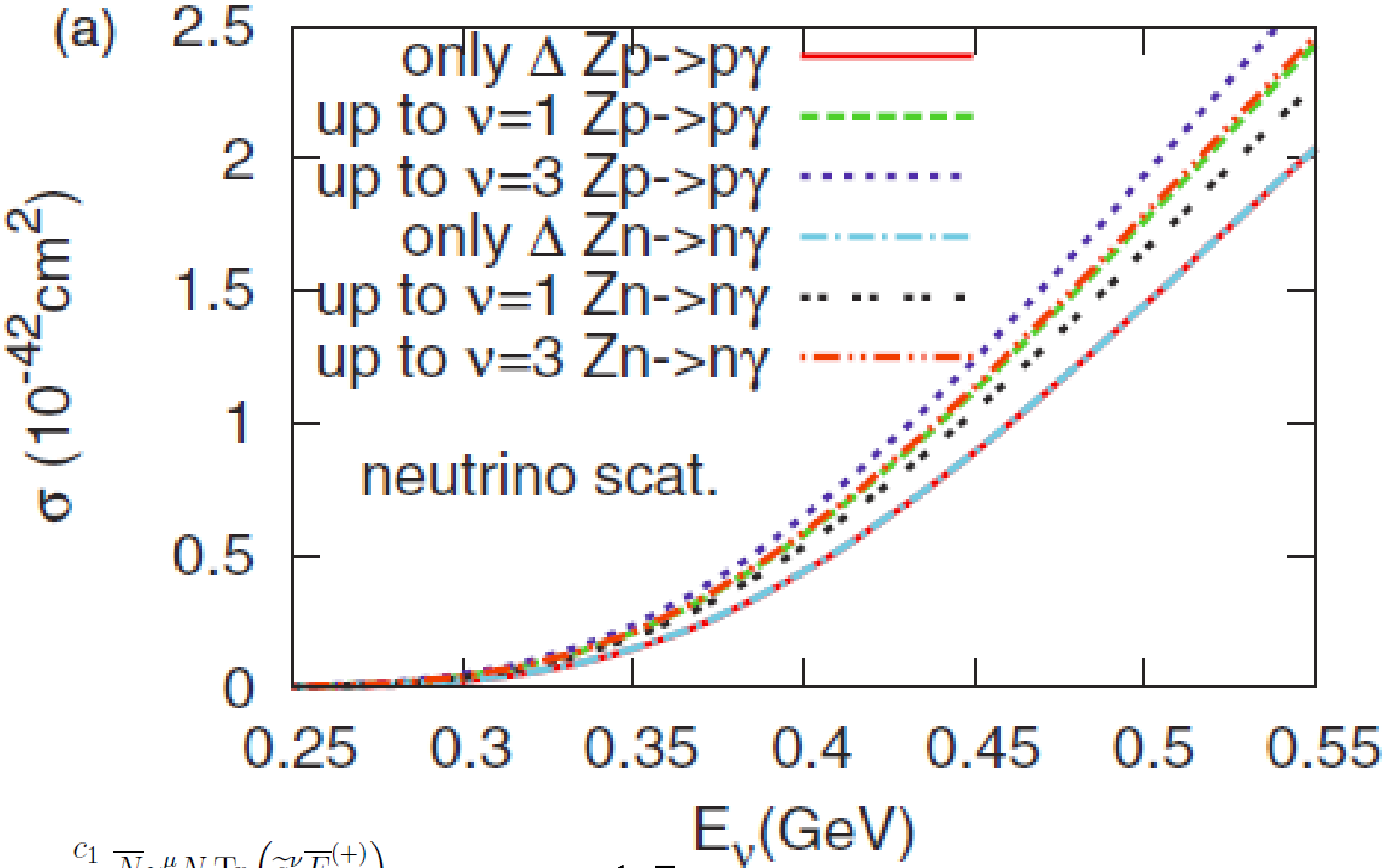
$$c_1 = 1.5$$

$$e_1 = 0.8$$

$$\langle J^\mu_{NC}\rangle_\gamma = \delta^A_B \frac{-iec_1}{M^2}\epsilon^{\mu\nu\alpha\beta}\bar{u}_f\gamma_\nu k_\alpha \epsilon^*_\beta(k)u_i + \delta^A_B\frac{-iec_1 q^\mu}{M^2(q^2-m_\pi^2)}\epsilon^{\lambda\nu\alpha\beta}\bar{u}_f\gamma_\lambda q_\nu k_\alpha \epsilon^*_\beta(k)u_i$$

N intermediate state $\sim \frac{1}{M}$

These terms are small



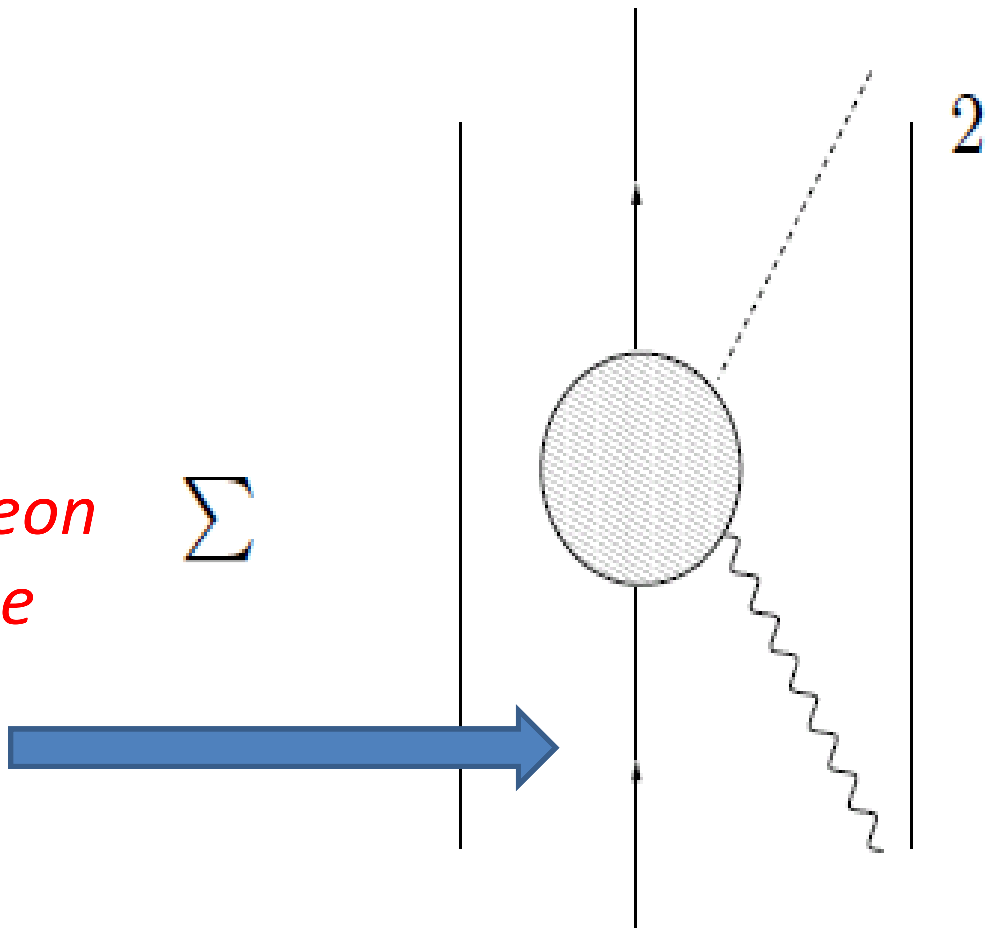
$$\frac{c_1}{M^2}\overline{N}\gamma^\mu N\,\mathrm{Tr}\left(\widetilde{a}^\nu \overline{F}^{(+)}_{\mu\nu}\right) , \qquad c_1 = 1.5$$

$$\frac{e_1}{M^2}\overline{N}\gamma^\mu \widetilde{a}^\nu N \overline{f}_{s\mu\nu} . \qquad e_1 = 0.8$$

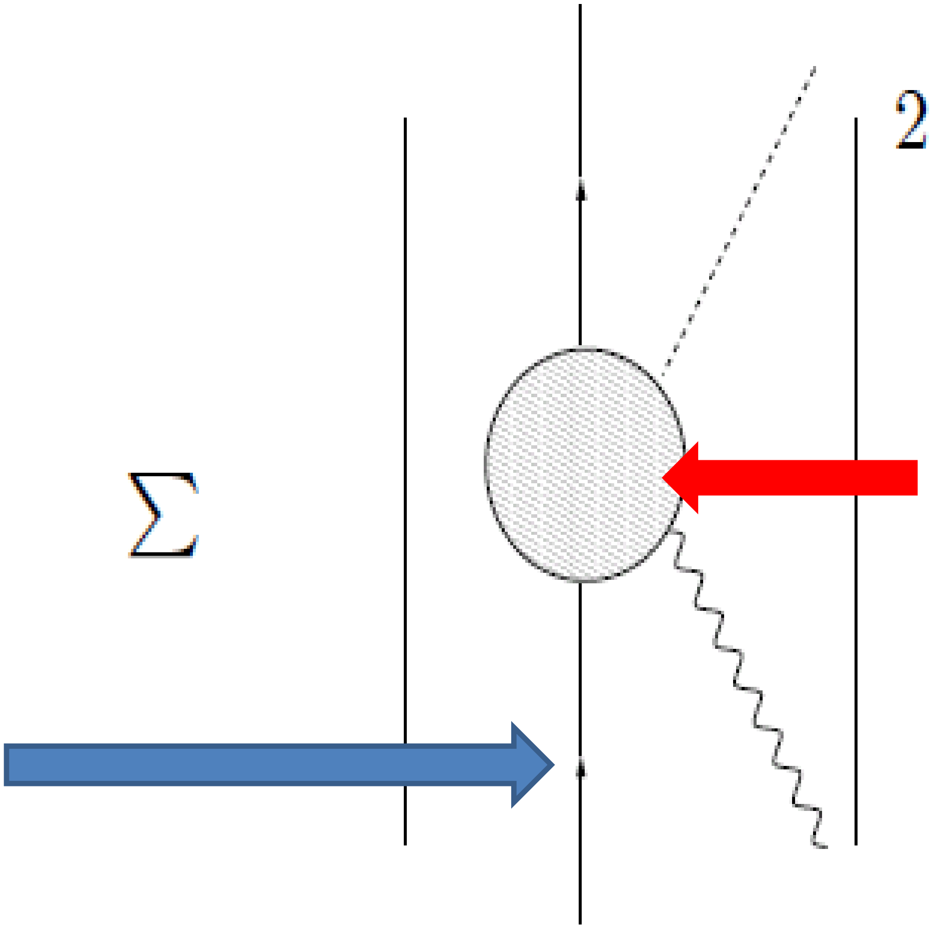
Nuclear effects in the incoherent and coherent productions

Incoherent productions

Initial nucleon (shell) wave function



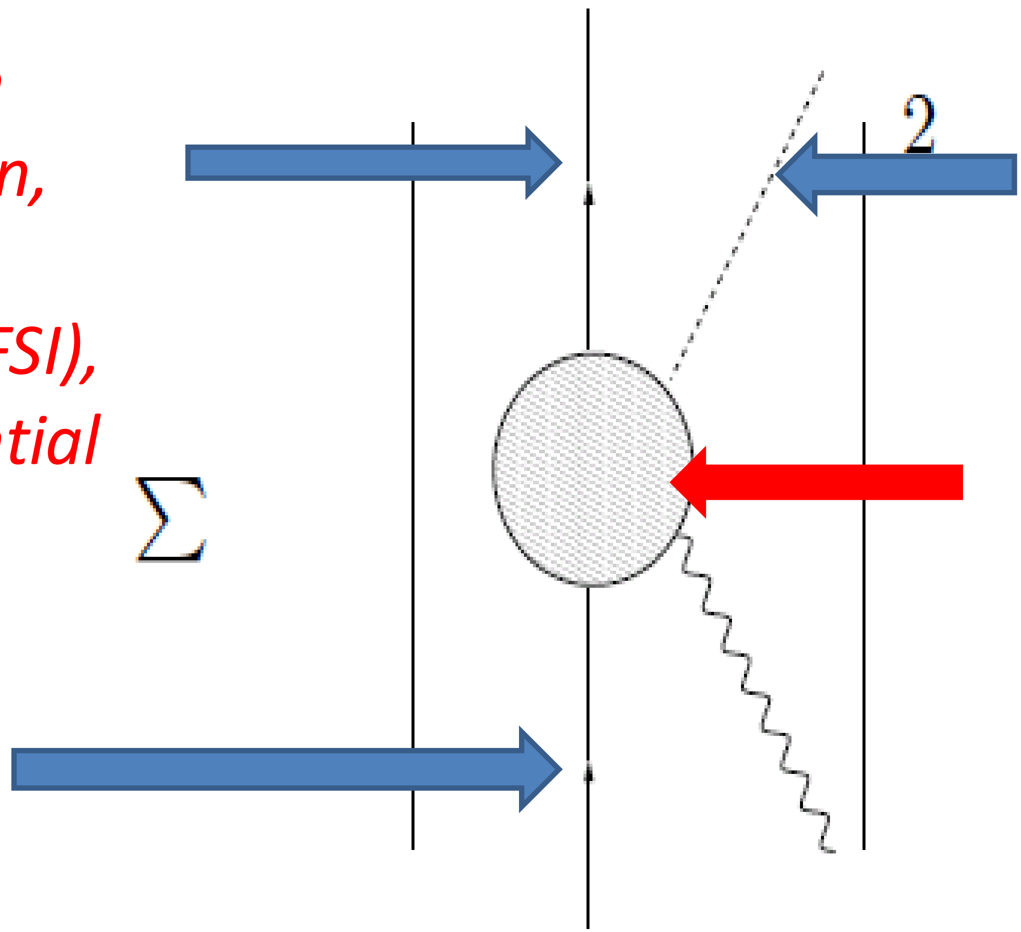
Incoherent productions



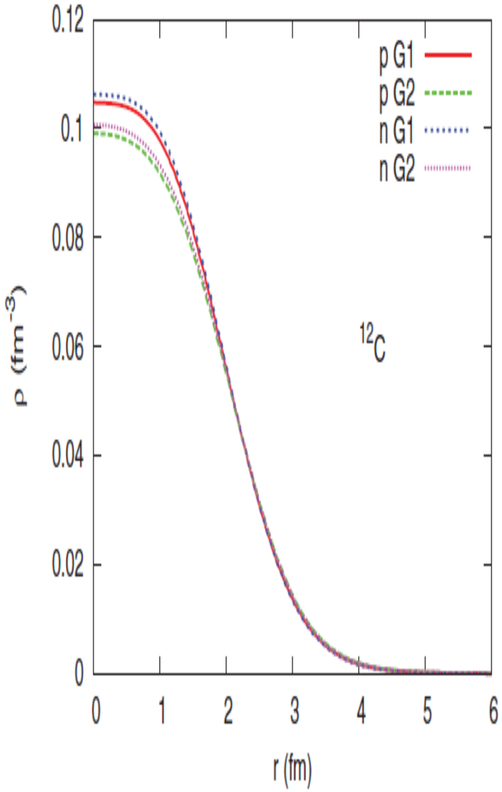
Medium modification of intermediate states: N and Delta

Incoherent productions

Final nucleon wave function, final state interaction (FSI), optical potential

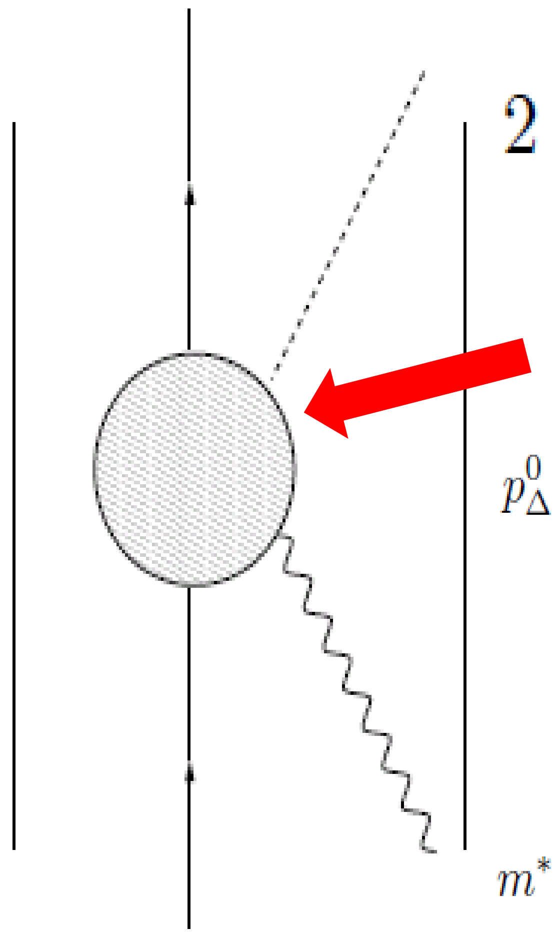


Pion FSI, optical potential; Photon has no FSI



Local Fermi Gas

$$\sum_{\vec{r}} \sum_{\vec{p}}^{k_F(\vec{r})}$$



$$\left| \cdots \right|^2$$

Delta:

$$p_\Delta^0 = h_v\langle V^0\rangle + \sqrt{m^{*2} + \vec{p}_\Delta^{\,2}}$$
$$\equiv h_v\langle V^0\rangle + p_\Delta^{*0}$$
$$= h_v\langle V^0\rangle + \sqrt{m^{*2} + \vec{p}_\Delta^{\,*2}}\,,$$
$$m^* \equiv m - h_s\langle\phi\rangle\,.$$

Nucleon:

$$E(\vec{p}) = \sqrt{\vec{p}^{\,2} + M^{*2}} + g_v\langle V^0\rangle$$
$$M^* = M - g_s\langle\phi\rangle$$

X.Z. and B. Serot, Phys. Rev. C 86, 035502 (2012) (arXiv: 1206.6324)

Delta in the nuclear medium

- Self energy: real part → spin-orbital coupling in nucleus

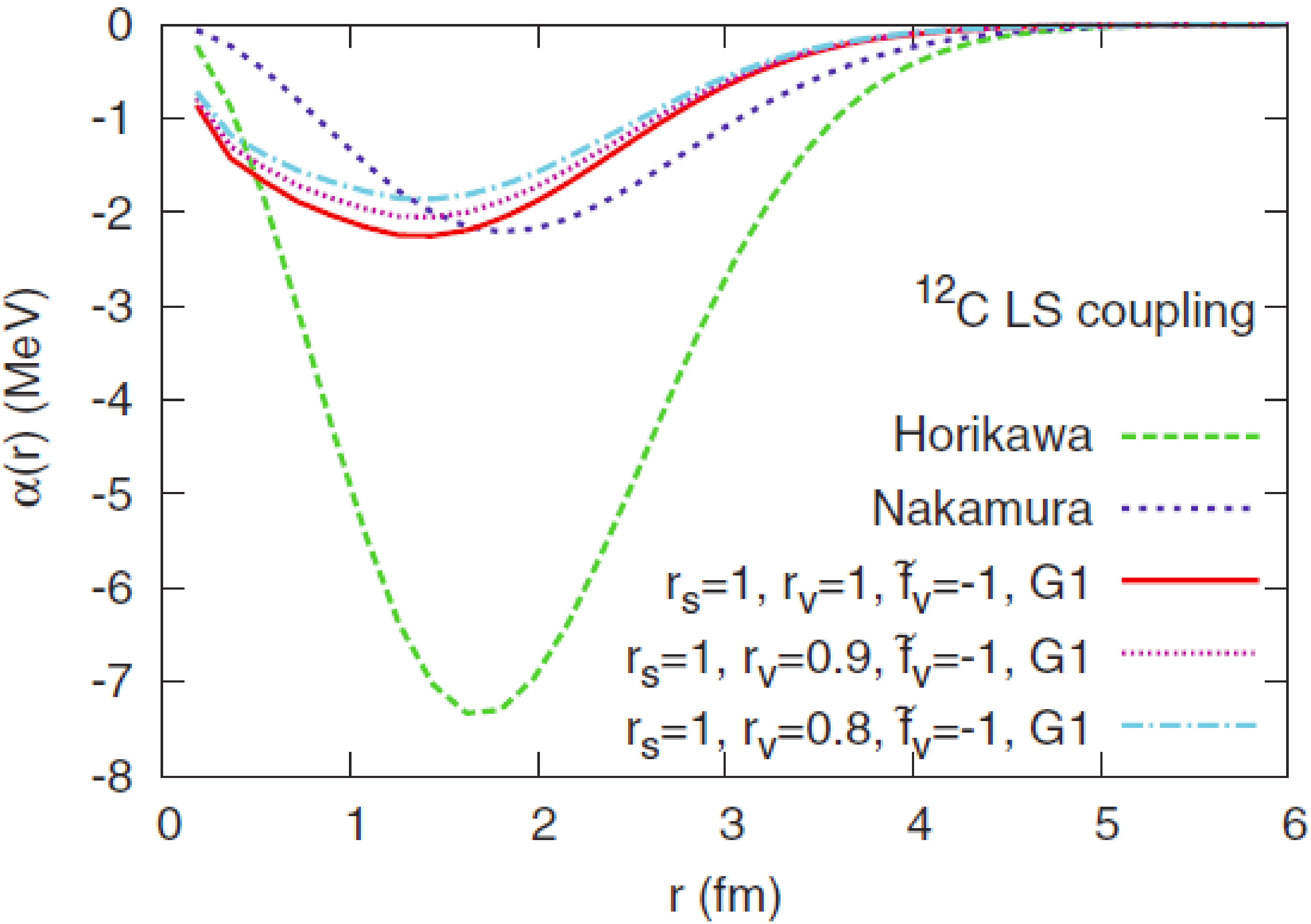
$$\mathcal{L}_{\Delta;\pi,\rho,V,\phi} = \frac{-i}{2}\overline{\Delta}^a_\mu \left\{\sigma^{\mu\nu} \, , \, \left(i\,\tilde{\partial\!\!\!/} - h_\rho\,\rho\!\!\!/ - h_v\,V\!\!\!\!/ - m + h_s\phi\right)\right\}^b_a \Delta_{b\nu}$$

$$h_\Delta = \frac{1}{3}\left[\frac{1}{2\overline{m}^2\;r}\frac{d}{dr}\left(h_s\langle\phi\rangle + h_v\langle V^0\rangle\right) - \frac{\tilde{f}_v}{m\overline{m}\;r}\frac{d}{dr}\left(h_v\langle V^0\rangle\right)\right]\vec{S}\cdot\vec{L}$$

$$\equiv \alpha(r)\vec{S}\cdot\vec{L}\,.$$

$$r_s = h_s / g_s$$

$$r_v = h_v / g_v$$



Y. Horikawa, M. Thies, and F. Lenz, Nucl.Phys.A ***345****, 386 (1980).*
S. X. Nakamura, T. Sato, T.-S. H. Lee, B. Szczerbinska, and K. Kubodera, Phys.Rev.C ***81****, 035502 (2010).*

Delta in the nuclear medium

- Self energy: real part → spin-orbital coupling in nucleus
- Self energy: imaginary part; collision broadening

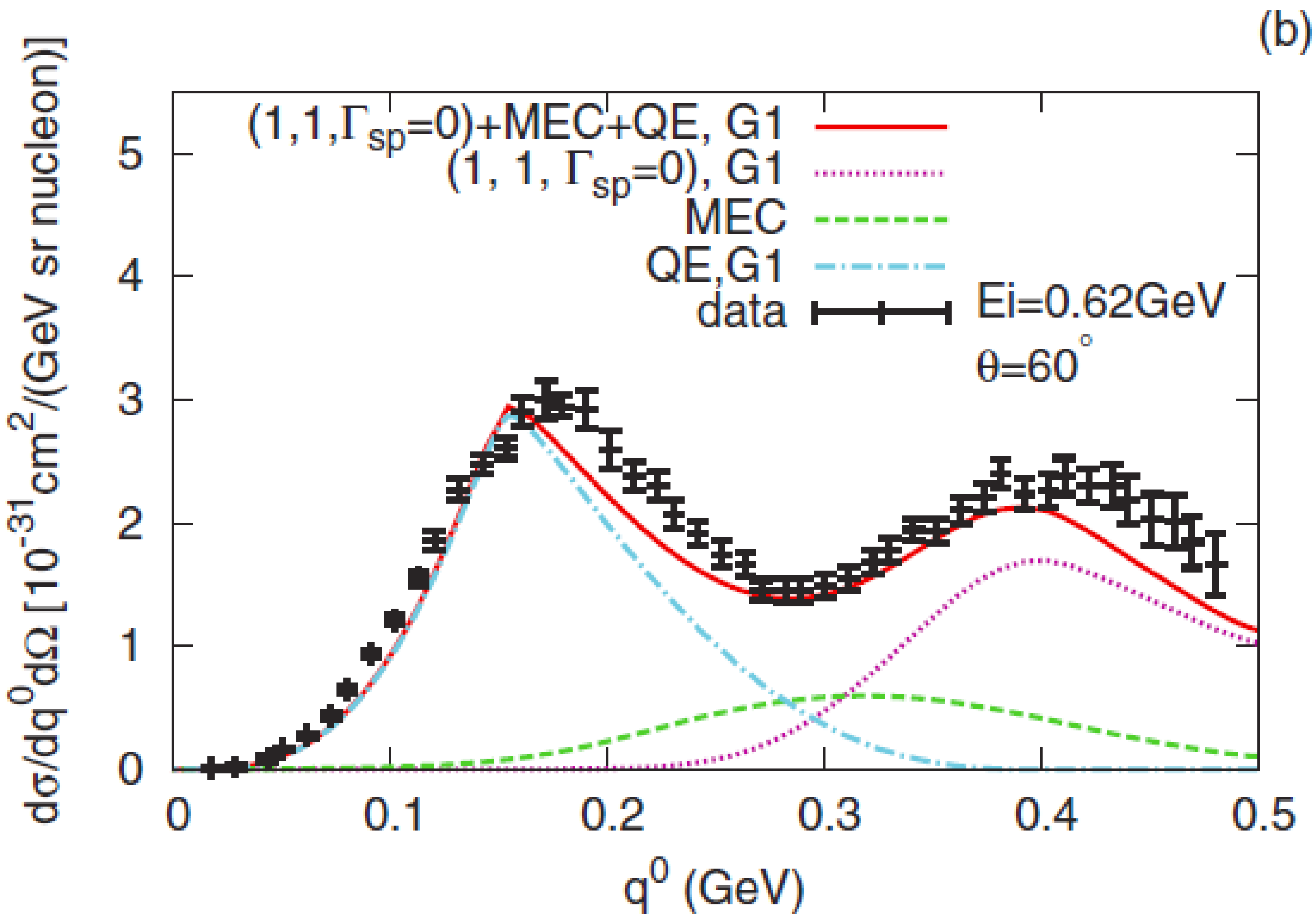
$$\Gamma_\Delta = \Gamma_\pi + \Gamma_{\rm sp} ,$$

$$\Gamma_{\rm sp} = V_0 \times \frac{\rho(r)}{\rho(0)}$$

$$V_0 \approx 80 \ \mathrm{MeV}$$

E. Oset and L. Salcedo, Nucl.Phys.A ***468****, 631 (1987)*

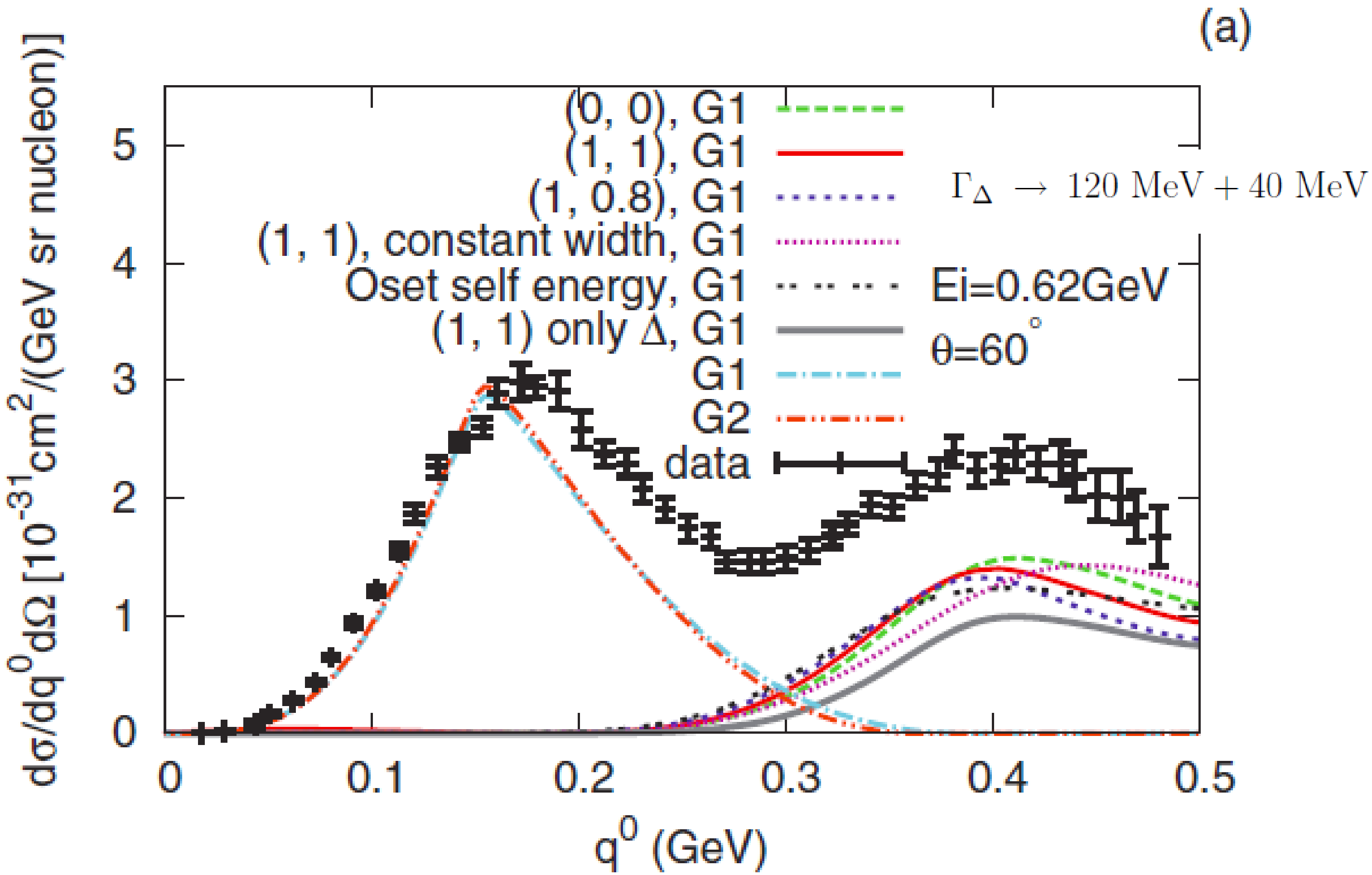
- Check: incoherent electro-production of pion from C12.



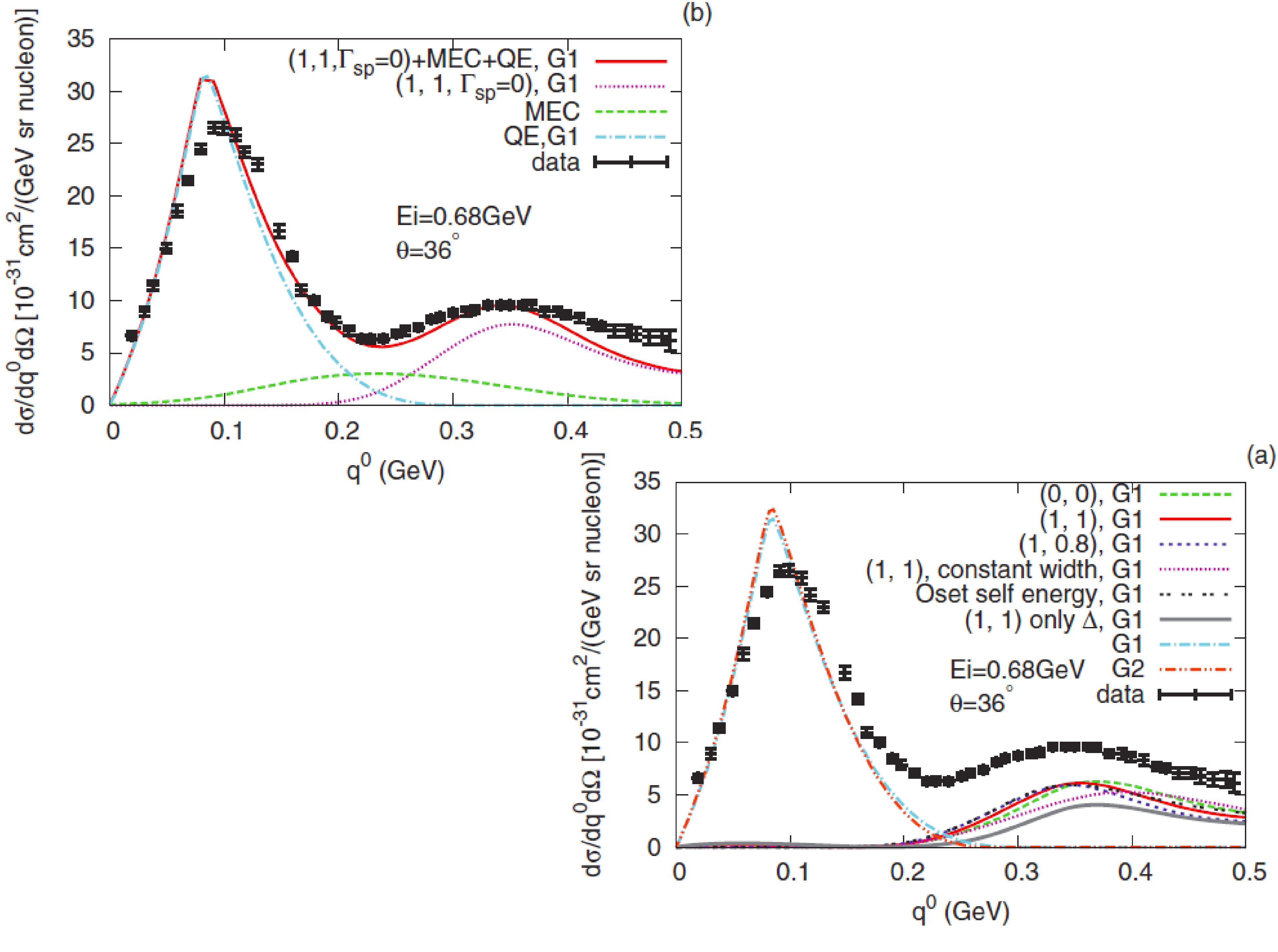
T. W. Donnelly (private communication).

P. Barreau et al., Nucl.Phys.A ***402****, 515 (1983).*

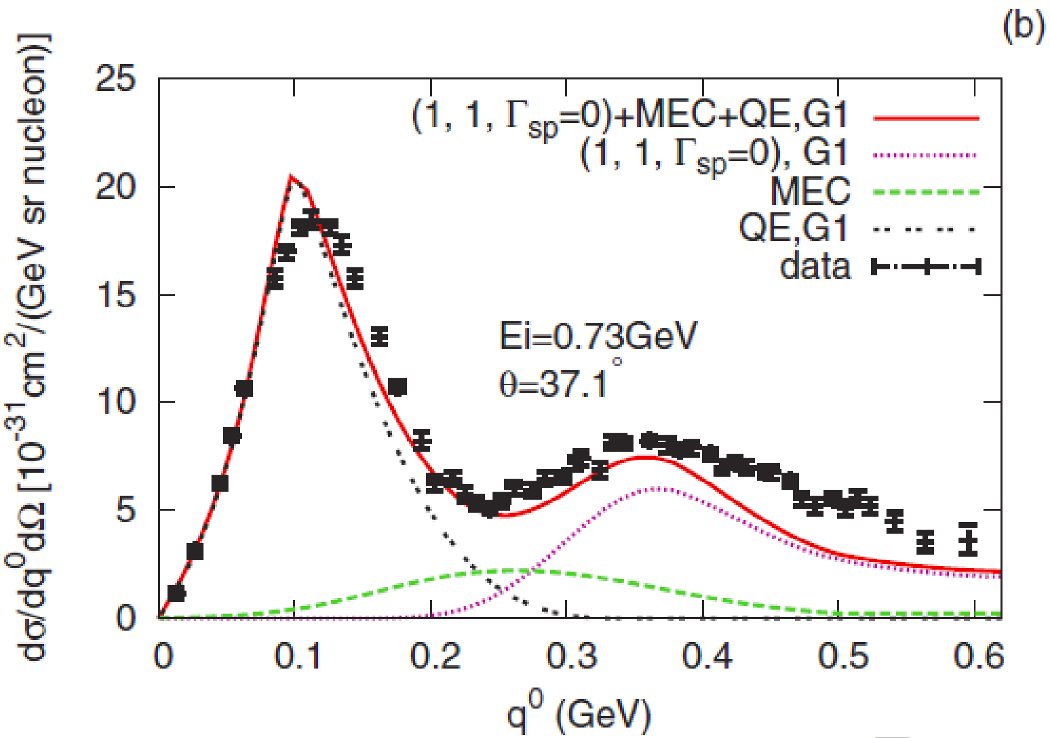
- Check: incoherent electro-production of pion from C12.

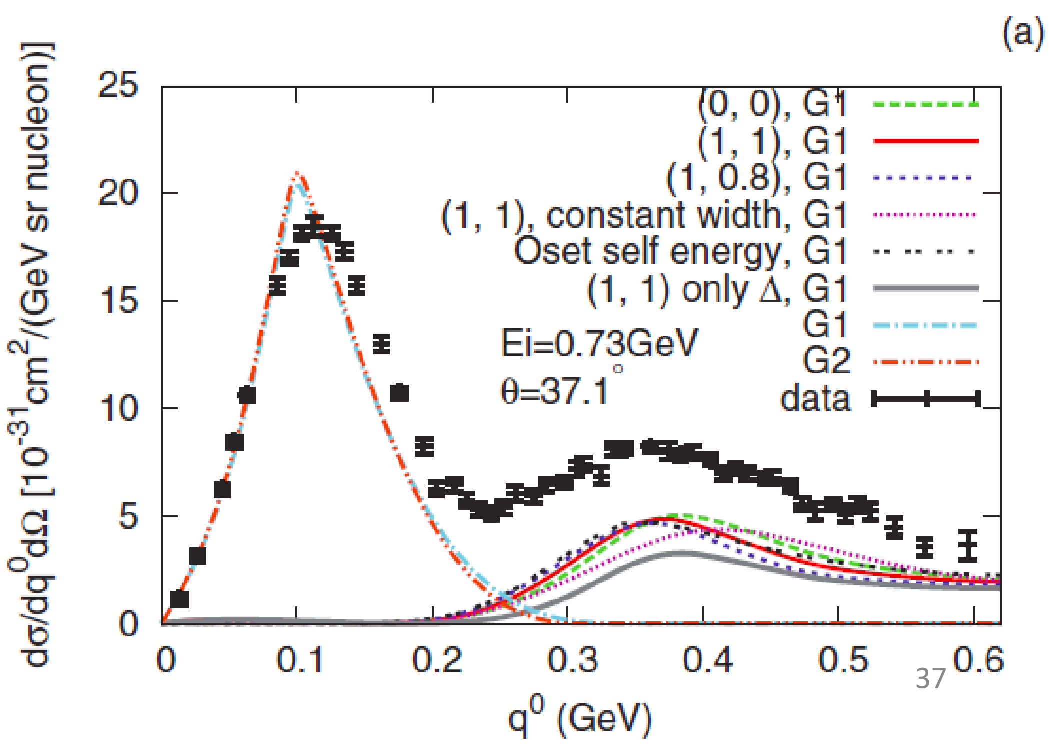


*P. Barreau et al., Nucl.Phys.A **402**, 515 (1983).*

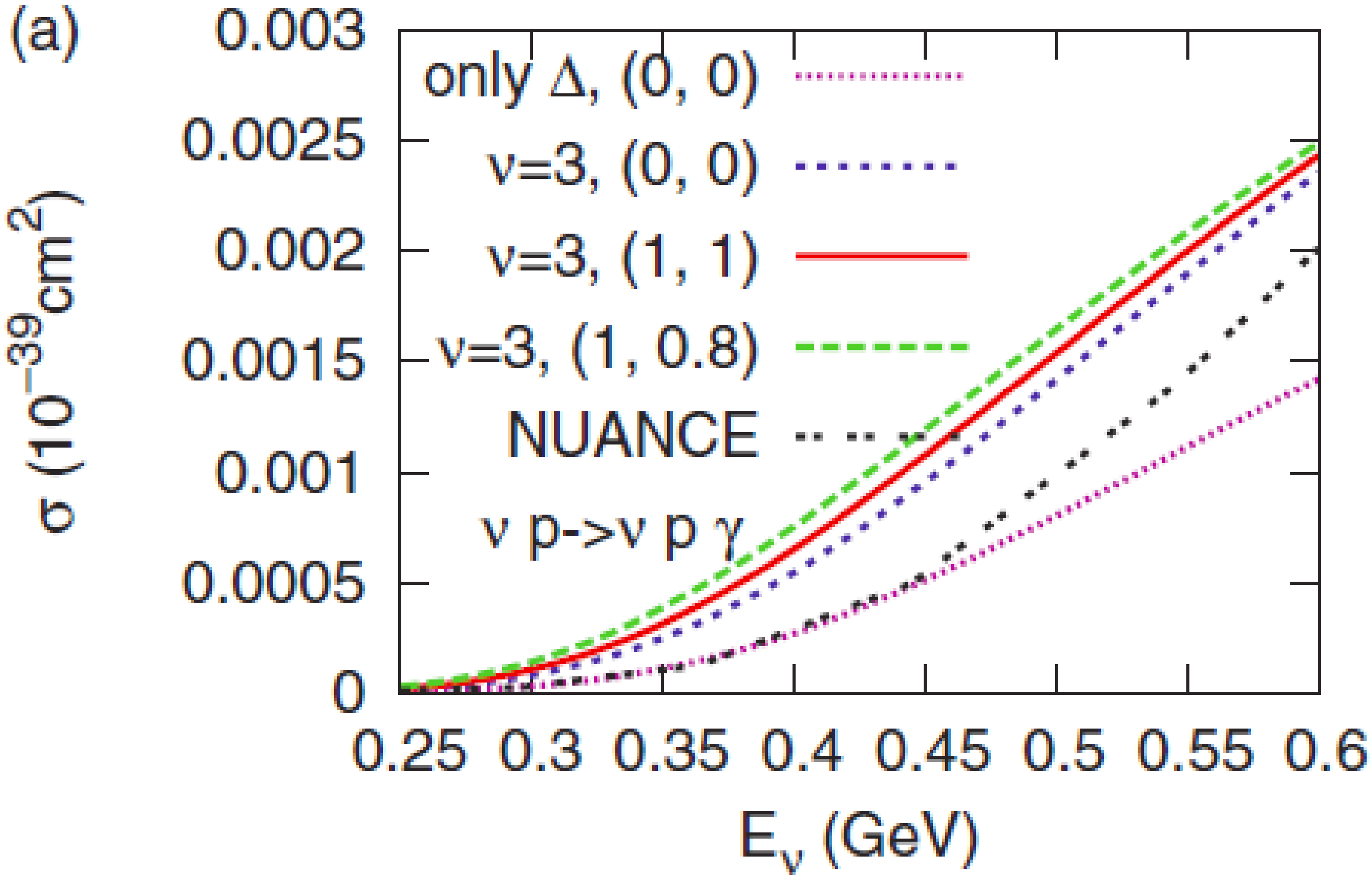


(b)
(1,1,Γsp=0)+MEC+QE, G1
(1, 1, Γsp=0), G1
MEC
QE,G1
data
Ei=0.68GeV
θ=36°
dσ/dq0dΩ [10-31cm2/(GeV sr nucleon)]
q0 (GeV)
(a)
(0, 0), G1
(1, 1), G1
(1, 0.8), G1
(1, 1), constant width, G1
Oset self energy, G1
(1, 1) only Δ, G1
G1
G2
data
Ei=0.68GeV
θ=36°
dσ/dq0dΩ [10-31cm2/(GeV sr nucleon)]
q0 (GeV)


(b)
(1, 1, Γsp=0)+MEC+QE,G1
(1, 1, Γsp=0), G1
MEC
QE,G1
data
Ei=0.73GeV
θ=37.1°
dσ/dq0dΩ [10-31cm2/(GeV sr nucleon)]
q0 (GeV)
0
5
10
15
20
25
0.1
0.2
0.3
0.4
0.5
0.6

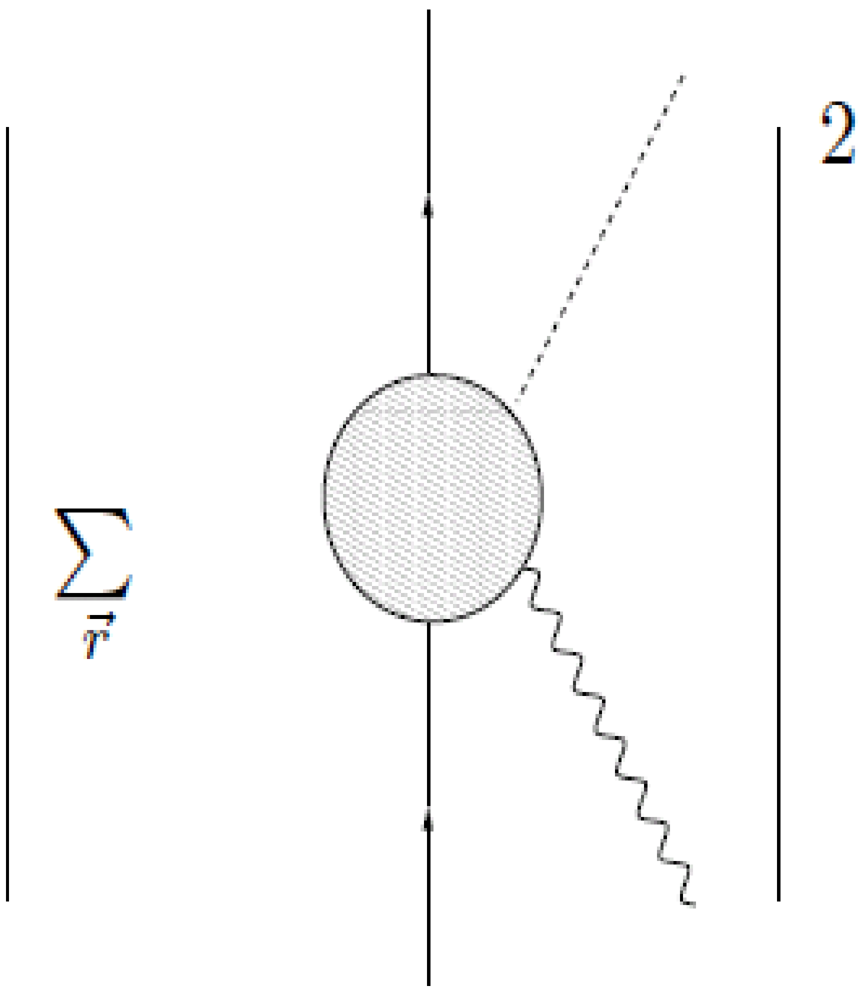

(a)
(0, 0), G1
(1, 1), G1
(1, 0.8), G1
(1, 1), constant width, G1
Oset self energy, G1
(1, 1) only Δ, G1
G1
G2
data
Ei=0.73GeV
θ=37.1°
dσ/dq0dΩ [10-31cm2/(GeV sr nucleon)]
q0 (GeV)
0
5
10
15
20
25
0.1
0.2
0.3
0.4
0.5
0.6

NC photon



(a)
σ (10^−39 cm^2)
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
only Δ, (0, 0)
ν=3, (0, 0)
ν=3, (1, 1)
ν=3, (1, 0.8)
NUANCE
ν p->ν p γ
0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6
E_ν (GeV)

Coherent production of pion



Coherent production of pion

- "Optimal" approximation (factorization): **?**

$$\frac{1}{m_A}\langle A,\pi(\vec{k}_\pi)|J^\mu_{had}|A\rangle$$

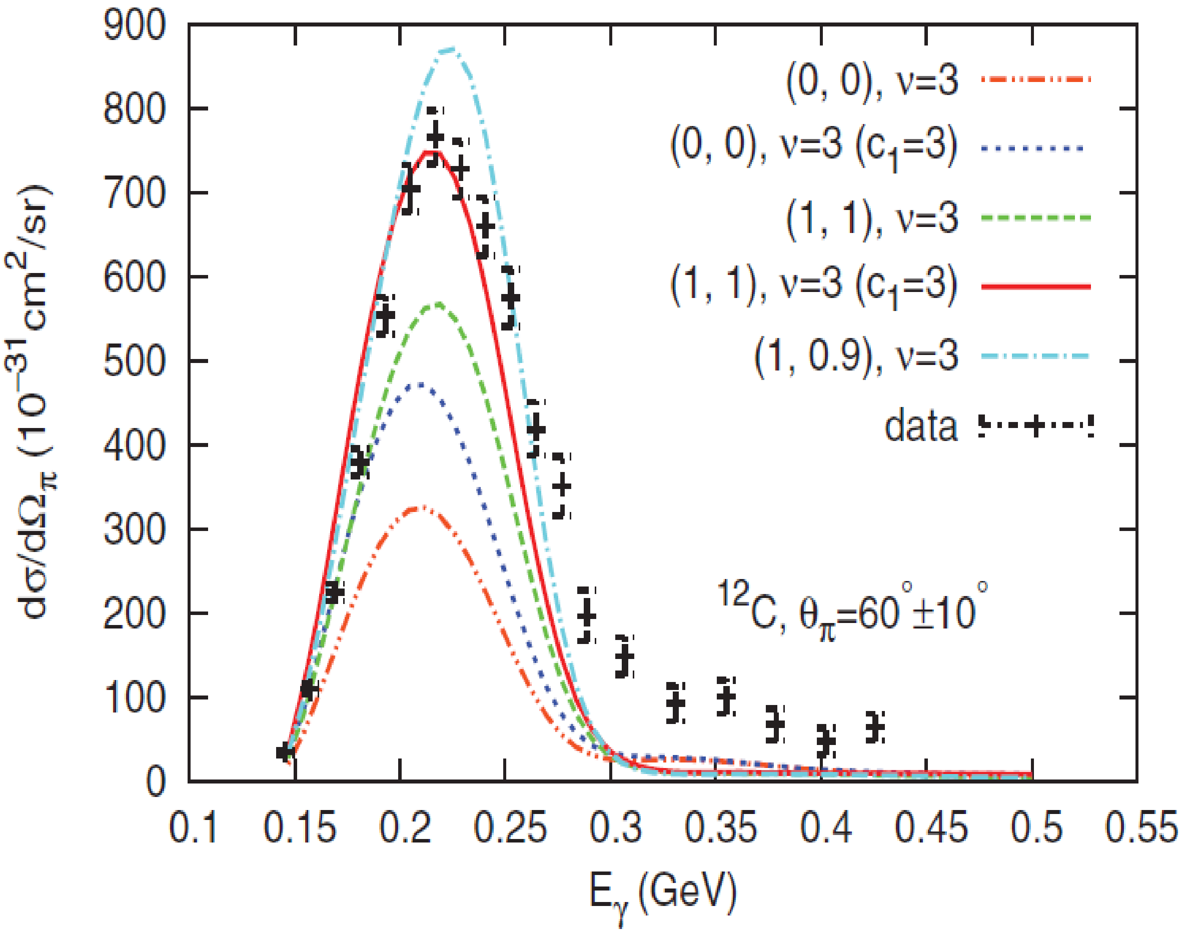
$$\approx \begin{cases} \int_A d\vec{r} e^{i(\vec{q}-\vec{k}_\pi)\cdot\vec{r}}\langle J^\mu_{had}(\vec{q},\vec{k}_\pi,\vec{r})\rangle & \text{PW}, \\ \int_A d\vec{r} e^{i(\vec{q}-\vec{k}_\pi)\cdot\vec{r}} e^{-i\int_z^\infty \frac{\Pi(\rho,l)}{2|\vec{k}_\pi|}dl}\langle J^\mu_{had}(\vec{q},\vec{k}_\pi,\vec{r})\rangle & \text{DW}. \end{cases}$$

X.Z. and B. Serot, PRC 86, 035504 (2012) arXiv:1208.1553)

$$\langle J^\mu_{had}(\vec{q},\vec{k}_\pi,\vec{r})\rangle \approx \rho_n(\vec{r})\frac{1}{2}\sum_{s_z}\frac{1}{p^{*0}_{ni}}\langle n, s_z, \frac{\vec{q}-\vec{k}_\pi}{2}|J^\mu_{had}(\vec{q},\vec{k}_\pi)|n, s_z, \frac{\vec{k}_\pi-\vec{q}}{2}\rangle$$

$$+\ \rho_p(\vec{r})\frac{1}{2}\sum_{s_z}\frac{1}{p^{*0}_{ni}}\langle p, s_z, \frac{\vec{q}-\vec{k}_\pi}{2}|J^\mu_{had}(\vec{q},\vec{k}_\pi)|p, s_z, \frac{\vec{k}_\pi-\vec{q}}{2}\rangle\ .$$

- photo-production of pions from C12.

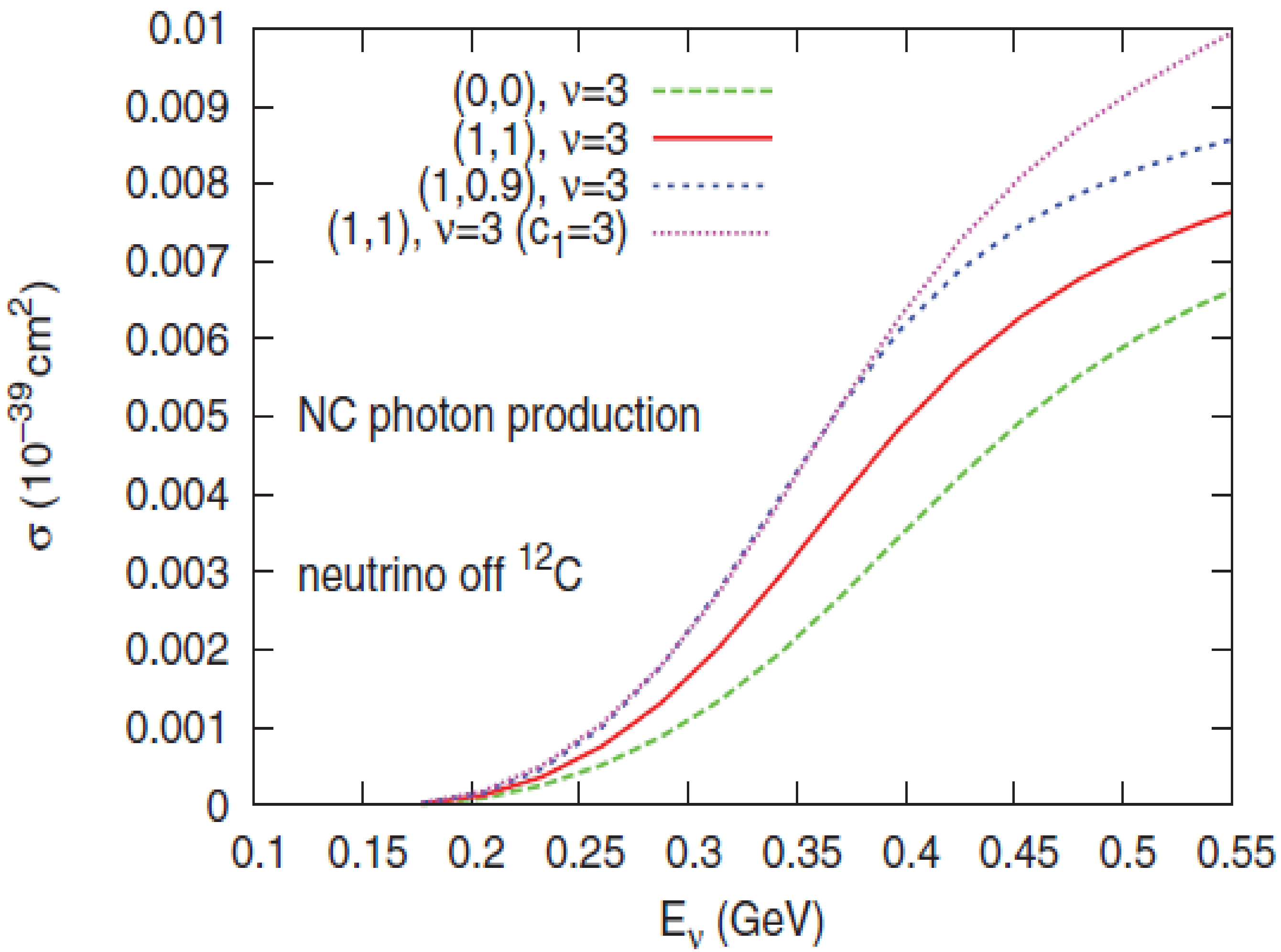


Also related to pion electro(photo)-production

$$\frac{c_1}{M^2}\overline{N}\gamma^\mu N\,\mathrm{Tr}(\widetilde{a}^\nu \overline{F}^{(+)}_{\mu\nu})\,, \quad \frac{e_1}{M^2}\overline{N}\gamma^\mu\widetilde{a}^\nu N\overline{f}_{s\mu\nu}\,.$$

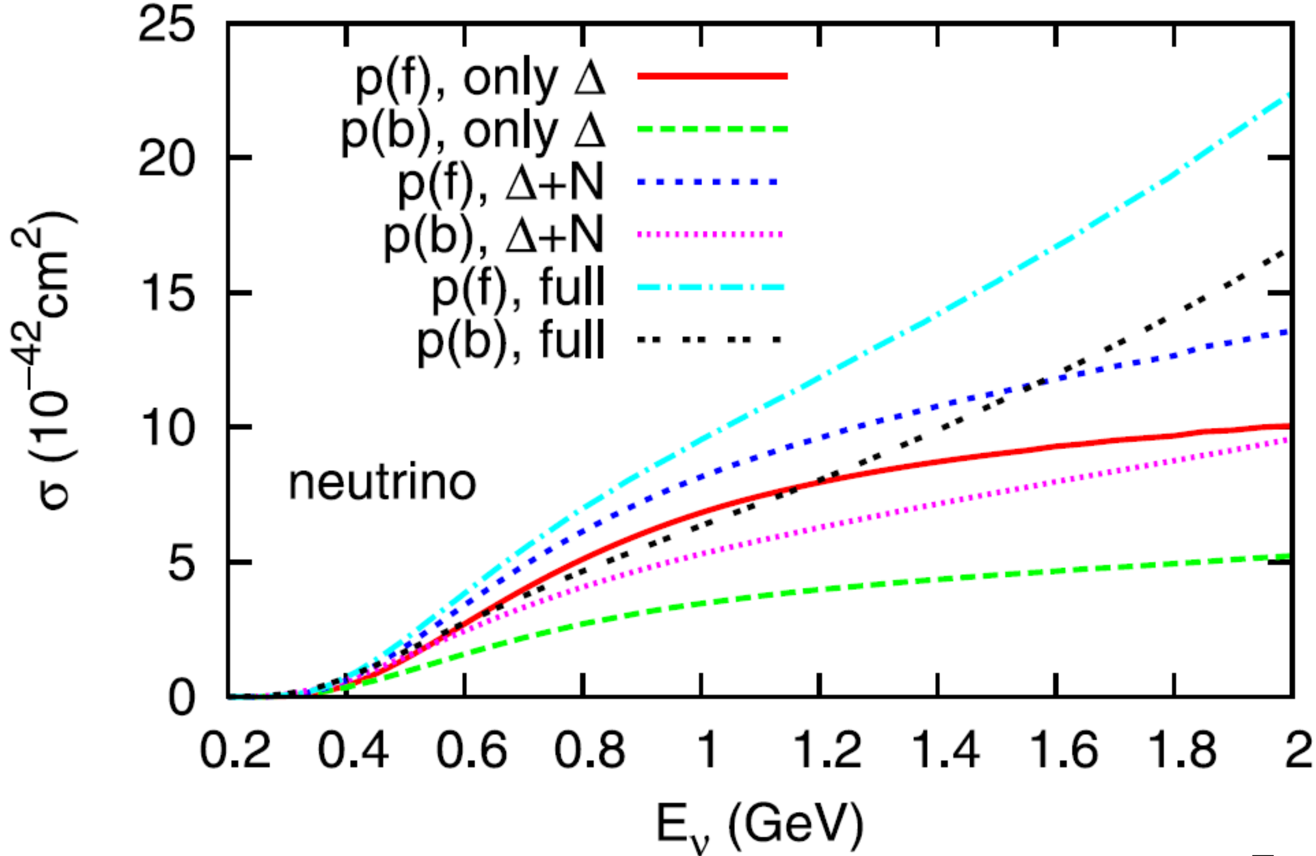
M. Schmitz, Ph.D. thesis, Johannes Gutenberg Universit¨at Mainz, 1996.
*W. Peters, H. Lenske, and U. Mosel, NPA **640**, 89 (1998).*

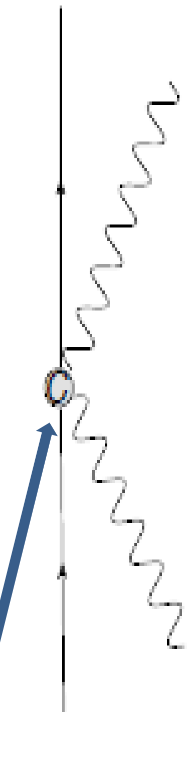
Coherent NC photon



MiniBooNE NC photon events: extrapolation to Enu~ GeV region

MiniBooNE NC photon

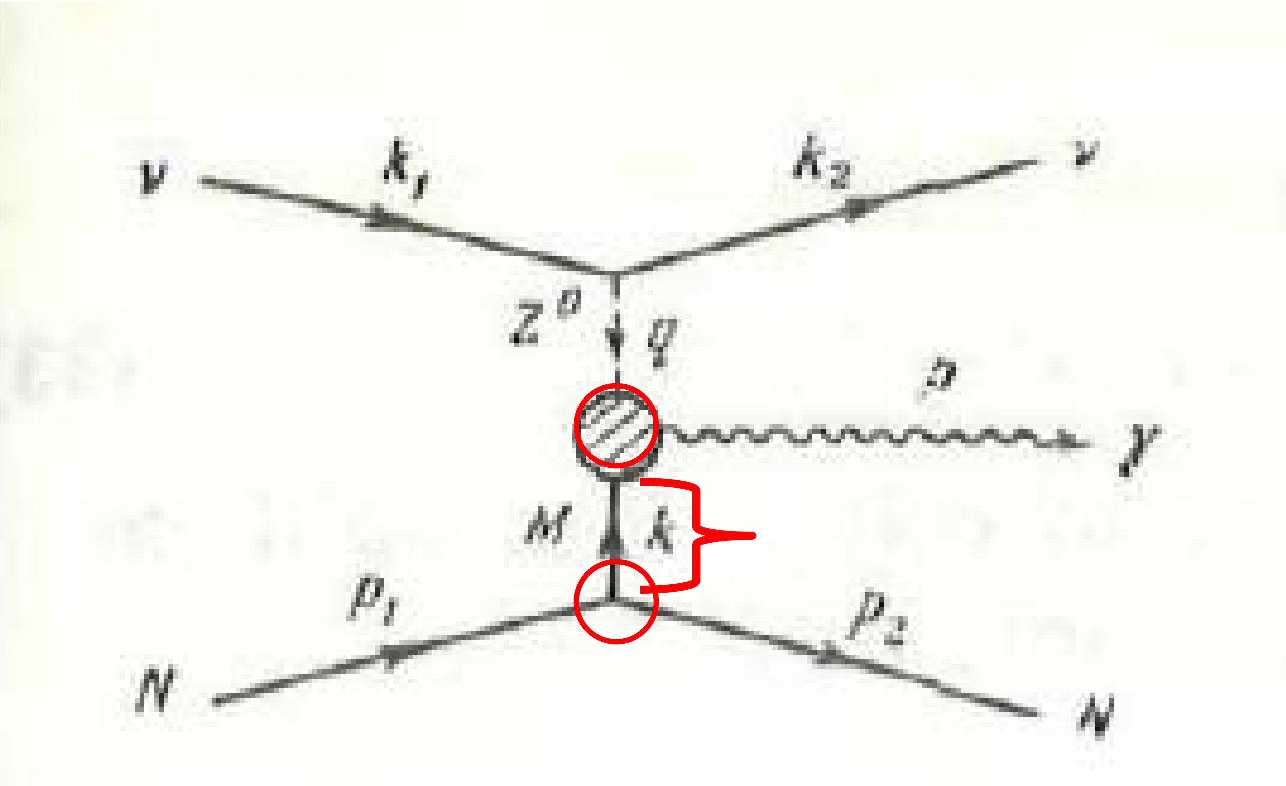


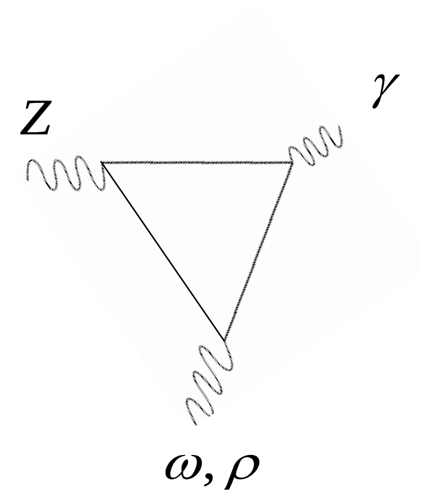


$$F(k^2) = \left[1 - \frac{k^2}{(1\,\mathrm{GeV})^2}\right]^{-3}$$

K. Graczyk, D. Kiełczewska, P. Przewłocki, and J. Sobczyk, Phys.Rev.D ***80****, 093001 (2009).*

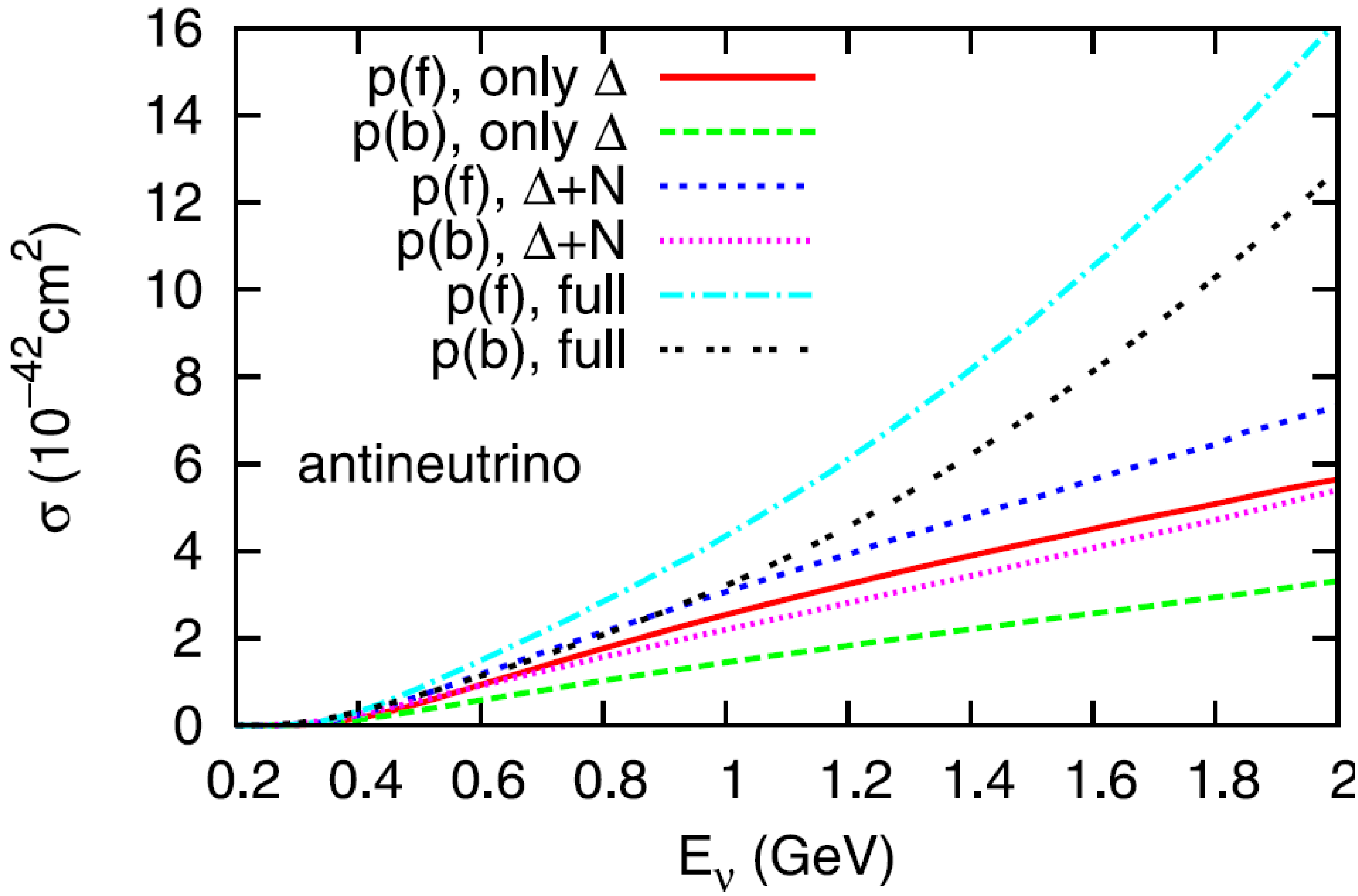
X.Z. and B. Serot, Phys.Lett.B 719, 409 (2013) (arXiv: 1210.3210)



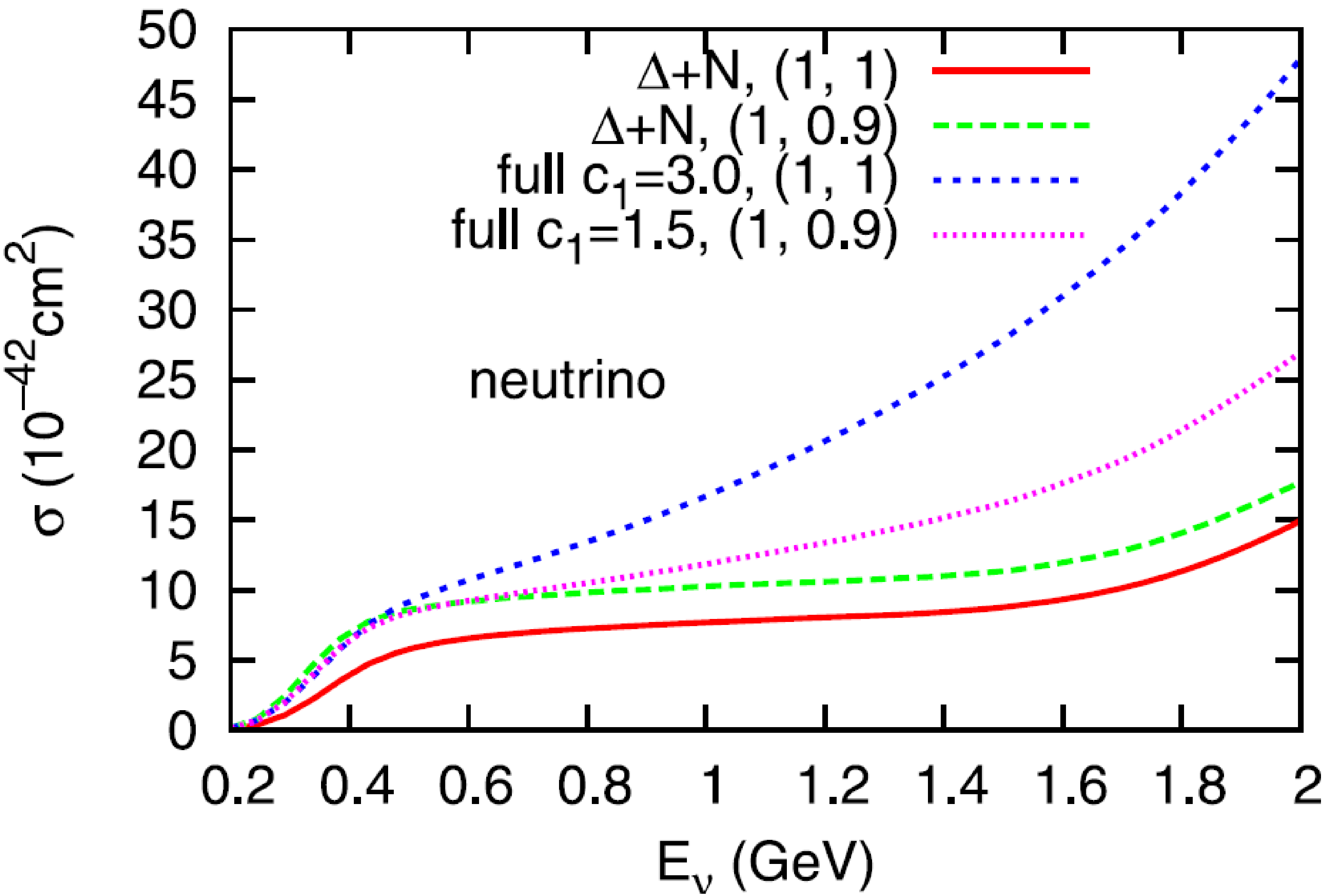


$$F(k^2) = \left[1 - \frac{k^2}{(1\,\mathrm{GeV})^2}\right]^{-3}$$

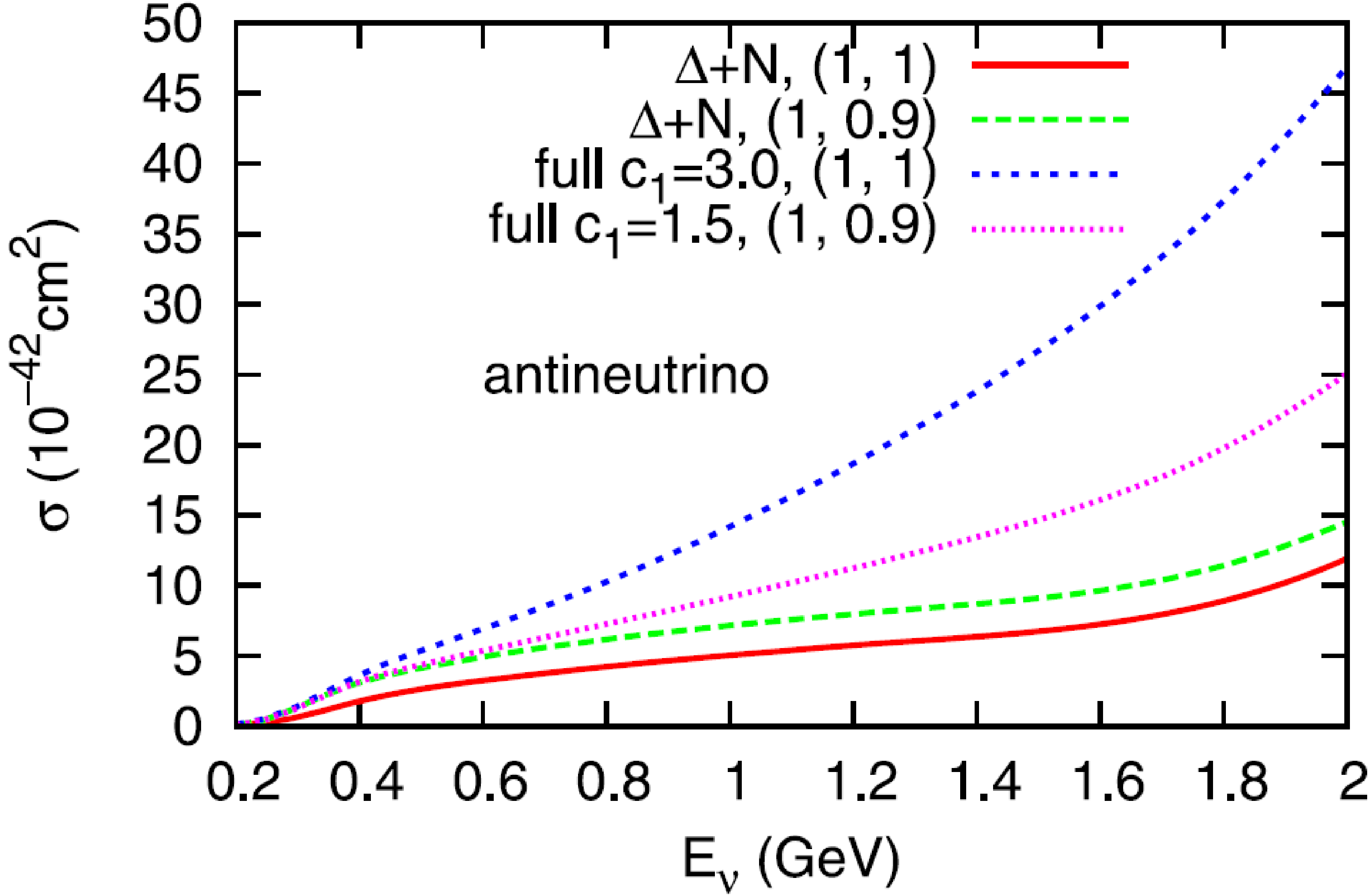
$$\left[1 - \frac{q^2}{(1\,\mathrm{GeV})^2}\right]^{-1} \quad ?$$



16
14
12
10
8
6
4
2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
σ (10^−42 cm^2)
E_ν (GeV)
p(f), only Δ
p(b), only Δ
p(f), Δ+N
p(b), Δ+N
p(f), full
p(b), full
antineutrino



50
45
40
35
30
25
20
15
10
5
0
σ (10^-42cm^2)
Δ+N, (1, 1)
Δ+N, (1, 0.9)
full c1=3.0, (1, 1)
full c1=1.5, (1, 0.9)
neutrino
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Eν (GeV)


Δ+N, (1, 1)
Δ+N, (1, 0.9)
full c1=3.0, (1, 1)
full c1=1.5, (1, 0.9)
antineutrino
σ (10^−42cm^2)
Eν (GeV)
0
5
10
15
20
25
30
35
40
45
50
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

MiniBooNE NC photon events

E_{QE}(GeV)	[0.2, 0.3]	[0.3, 0.475]	[0.475, 1.25]
coh	1.5 (2.9)	6.0 (9.2)	2.1 (8.0)
inc	12.0 (14.1)	25.5 (31.1)	12.6 (23.2)
H	4.1 (4.4)	10.6 (11.6)	4.6 (6.3)
Total	17.6 (21.4)	42.1 (51.9)	19.3 (37.5)
MiniBN	19.5	47.3	19.4
Excess	42.6 ± 25.3	82.2 ± 23.3	21.5 ± 34.9

E_{QE}(GeV)	[0.2, 0.3]	[0.3, 0.475]	[0.475, 1.25]
coh	1.0 (2.2)	3.1 (5.5)	0.87 (5.4)
inc	4.5 (5.3)	10.0 (12.2)	4.0 (10.2)
H	1.3 (1.6)	3.6 (4.3)	1.1 (2.4)
Total	6.8 (9.1)	16.7 (22.0)	6.0 (18.0)
MiniBN	8.8	16.9	6.8
Excess	34.6 ± 13.6	23.5 ± 13.4	20.2 ± 22.8

Xection needs to be doubled at least.

MiniBooNE NC photon events

E_γ(GeV)	coh	inc	H	Total	MiniBN	Excess
[0.1 , 0.2]	0.72 (1.5)	14.0 (15.0)	4.4 (4.6)	19.1 (21.1)	10.6	52.5
[0.2 , 0.3]	3.2 (5.5)	22.7 (25.2)	7.8 (8.5)	33.7 (39.2)	32.5	61.2
[0.3 , 0.4]	3.7 (5.4)	12.7 (15.0)	5.0 (5.6)	21.4 (26.0)	24.7	58.4
[0.4 , 0.5]	1.0 (1.7)	5.4 (7.3)	2.1 (2.4)	8.5 (11.4)	12.7	−9.7
[0.5 , 0.6]	0.32 (1.0)	2.3 (3.9)	0.75 (1.0)	3.4 (5.9)	4.4	10.5

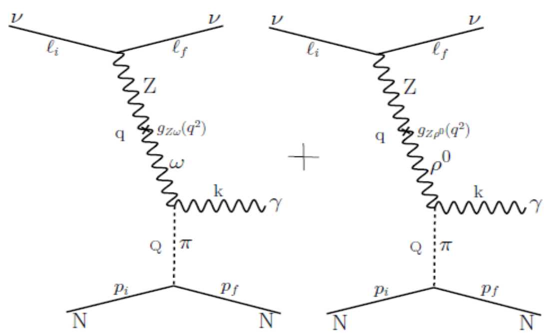
E_γ(GeV)	coh	inc	H	Total	MiniBN	Excess
[0.1 , 0.2]	0.55 (1.2)	4.9 (5.5)	1.4 (1.6)	6.9 (8.3)	4.3	18.8
[0.2 , 0.3]	2.0 (3.8)	8.7 (10.3)	2.9 (3.3)	13.6 (17.4)	14.3	22.6
[0.3 , 0.4]	1.8 (3.0)	4.0 (5.4)	1.5 (1.8)	7.3 (10.2)	9.1	11.5
[0.4 , 0.5]	0.36 (1.0)	1.3 (2.6)	0.43 (0.66)	2.1 (4.3)	3.6	18.7
[0.5 , 0.6]	0.10 (0.72)	0.51 (1.7)	0.14 (0.36)	0.75 (2.8)	1.1	8.4

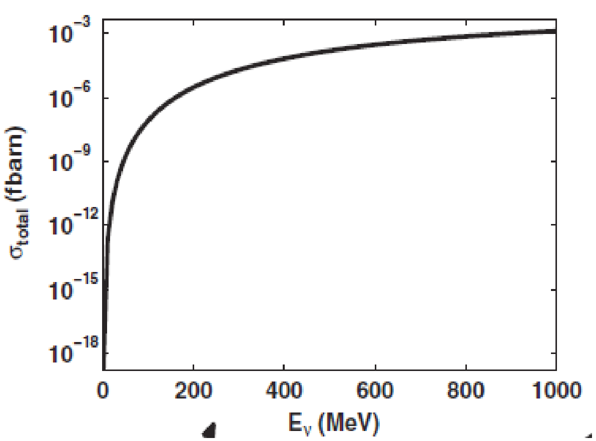
Proceedings of the DPF-2009 Conference, Detroit, MI, July 27-31, 2009

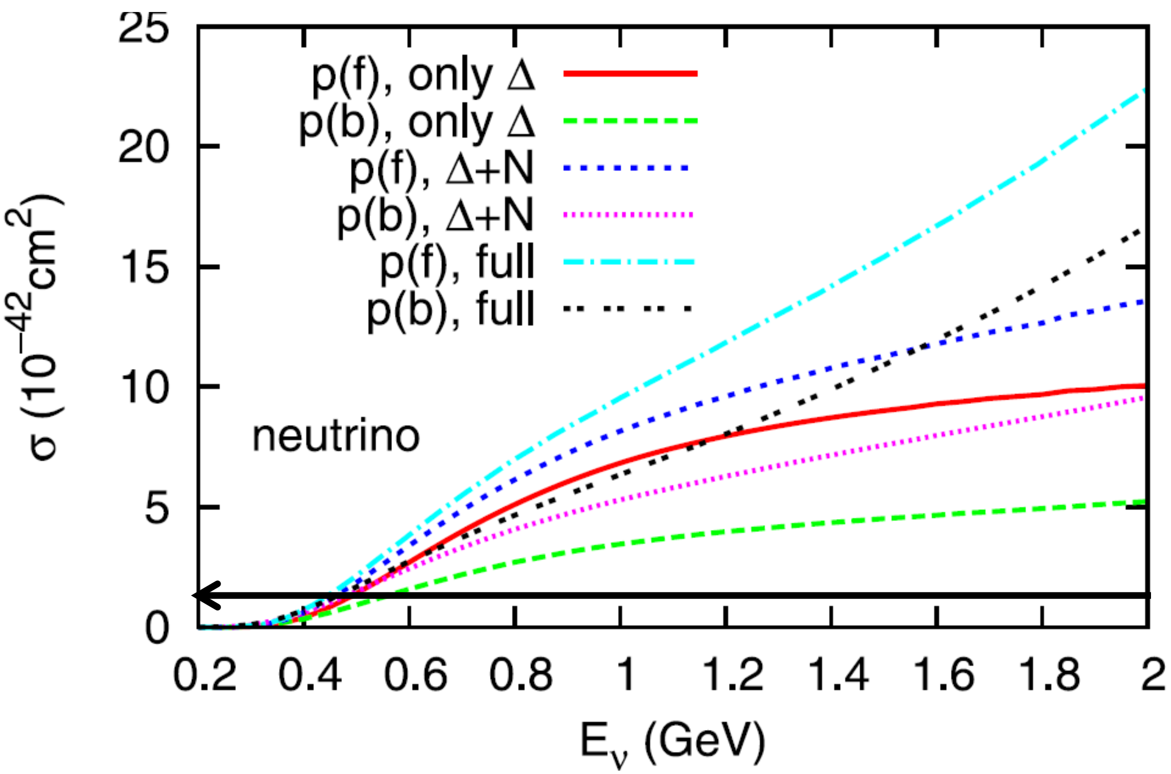
A phenomenological study of photon production in low energy neutrino nucleon scattering

James Jenkins and T. Goldman
Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

- Incoherent one is small at Enu~ 1 GeV
- Coherent one is zero







Summary and questions

- QHD→ bound state, electroweak currents, pion dynamics, baryon spectrum modification
- Reaction kernel, medium modification, and approximation schemes
- NC photon event at MiniBooNE
- Axial transition form factors?
- The contact term: couplings and form factors?
- LFG and optimal factorization?
- Experimental measurement?
- Would photon production help constrain FSIs?

Back up

A quick look:

- Chiral symmetry in QCD: $SU(2)_L \otimes SU(2)_R \otimes U(1)_B$

$$\mathcal{L} = \mathcal{L}_{QCD} + \bar{q}\gamma_\mu(\mathrm{v}^\mu + B\mathrm{v}^\mu_{(s)} + \gamma_5 \mathrm{a}^\mu)q - \bar{q}(\mathrm{s} - i\gamma_5 \mathrm{p})q$$

$$q_{LA} \to \exp\left[-i\frac{\theta(x)}{3}\right]\left(\exp\left[-i\theta_{Li}(x)\frac{\tau^i}{2}\right]\right)_A^{\ B} q_{LB} \equiv \exp\left[-i\frac{\theta(x)}{3}\right](L)_A^{\ B} q_{LB}\,,$$

$$q_R \to \exp\left[-i\frac{\theta(x)}{3}\right]\exp\left[-i\theta_{Ri}(x)\frac{\tau^i}{2}\right] q_R \equiv \exp\left[-i\frac{\theta(x)}{3}\right] R q_R\,,$$

CVC and (P)CAC

A quick look:

- Chiral symmetry in QCD:
- Its nonlinear realization at low energy EFT:

$$U \equiv \exp\left[2i\frac{\pi_i(x)}{f_\pi}t^i\right] \to LUR^\dagger ,$$

symmetry spontaneous breaking

$$\xi \equiv \sqrt{U} = \exp\left[i\frac{\pi_i}{f_\pi}t^i\right] \to L\xi h^\dagger = h\,\xi R^\dagger ,$$

$$\tilde{v}_\mu \equiv \frac{-i}{2}[\xi^\dagger(\partial_\mu - il_\mu)\xi + \xi(\partial_\mu - ir_\mu)\xi^\dagger] \equiv \tilde{v}_{i\mu}t^i \to h\,\tilde{v}_\mu h^\dagger - ih\,\partial_\mu h^\dagger ,$$

$$\tilde{a}_\mu \equiv \frac{-i}{2}[\xi^\dagger(\partial_\mu - il_\mu)\xi - \xi(\partial_\mu - ir_\mu)\xi^\dagger] \equiv \tilde{a}_{i\mu}t^i \to h\,\tilde{a}_\mu h^\dagger ,$$

A quick look:

- Chiral symmetry in QCD:
- Its nonlinear realization at low energy EFT:

$$(\widetilde{\partial}_\mu \psi)_\alpha \equiv (\partial_\mu + i\,\widetilde{v}_\mu - i v_{(s)\mu} B)_\alpha^{\ \beta} \psi_\beta \to \exp\left[-i\theta(x) B\right] h_\alpha^{\ \beta} (\widetilde{\partial}_\mu \psi)_\beta \,,$$

$$\widetilde{v}_{\mu\nu} \equiv -i[\widetilde{a}_\mu \,, \widetilde{a}_\nu] \to h\,\widetilde{v}_{\mu\nu} h^\dagger \,,$$

$$F^{(+)}_{\mu\nu} \equiv \xi^\dagger f_{L\mu\nu}\,\xi + \xi f_{R\mu\nu}\,\xi^\dagger \to h F^{(+)}_{\mu\nu} h^\dagger \,,$$

$$F^{(-)}_{\mu\nu} \equiv \xi^\dagger f_{L\mu\nu}\,\xi - \xi f_{R\mu\nu}\,\xi^\dagger \to h F^{(-)}_{\mu\nu} h^\dagger \,,$$

A quick look:

- The lagrangian, baryon section:

$$\mathcal{L}_{N(\hat{\nu}\leqslant 3)} = \overline{N}(i\gamma^{\mu}[\widetilde{\partial}_{\mu} + ig_{\rho}\rho_{\mu} + ig_{v}V_{\mu}] + g_{A}\gamma^{\mu}\gamma^{5}\widetilde{a}_{\mu} - M + g_{s}\phi)N$$

$$\mathcal{L}_{\Delta} = \frac{-i}{2}\overline{\Delta}_{\mu}^{a}\{\sigma^{\mu\nu}, (i\ \widetilde{\not{\partial}} - h_{\rho}\ \not{\rho} - h_{v}\ \not{V} - m + h_{s}\phi)\}_{a}^{b}\,\Delta_{b\nu}$$

$$\mathcal{L}_{\Delta,N,\pi} = h_{A}\overline{\Delta}^{a\mu}\,T_{a}^{\dagger iA}\,\widetilde{a}_{i\mu}N_{A} + \text{c.c.},$$

A quick look:

- The lagrangian, baryon section.
- The lagrangian, meson section:

$$\mathcal{L}_{\text{meson}(\hat{\nu}\leqslant 4)} = \tfrac{1}{2}\,\partial_\mu\phi\,\partial^\mu\phi + \tfrac{1}{4} f_\pi^2\,\mathrm{Tr}[\widetilde{\partial}_\mu U(\widetilde{\partial}^\mu U)^\dagger]$$
$$+ \tfrac{1}{4} f_\pi^2 m_\pi^2\,\mathrm{Tr}(U + U^\dagger - 2)$$
$$- \tfrac{1}{2}\,\mathrm{Tr}(\rho_{\mu\nu}\rho^{\mu\nu}) - \tfrac{1}{4} V^{\mu\nu} V_{\mu\nu}$$
$$+ \frac{1}{2g_\gamma}\left(\mathrm{Tr}(F^{(+)\mu\nu}\rho_{\mu\nu}) + \tfrac{1}{3} f_s^{\mu\nu} V_{\mu\nu}\right).$$

Vector meson dominanc e (VMD)

A quick look:

- Electroweak (EW) interactions:

$$
\begin{aligned}
l_\mu &= -e\,\frac{\tau^0}{2}\,A_\mu + \frac{g}{\cos\theta_w}\sin^2\theta_w\,\frac{\tau^0}{2}\,Z_\mu \\
&\quad - \frac{g}{\cos\theta_w}\frac{\tau^0}{2}\,Z_\mu - gV_{ud}\left(W_\mu^{+1}\,\frac{\tau_{+1}}{2} + W_\mu^{-1}\frac{\tau_{-1}}{2}\right), \\
r_\mu &= -e\,\frac{\tau^0}{2}\,A_\mu + \frac{g}{\cos\theta_w}\sin^2\theta_w\,\frac{\tau^0}{2}\,Z_\mu\,, \\
\mathrm{v}_{(s)\mu} &= -e\,\frac{1}{2}\,A_\mu + \frac{g}{\cos\theta_w}\sin^2\theta_w\,\frac{1}{2}\,Z_\mu\,.
\end{aligned}
$$

A quick look:

- Electroweak (EW) interactions:

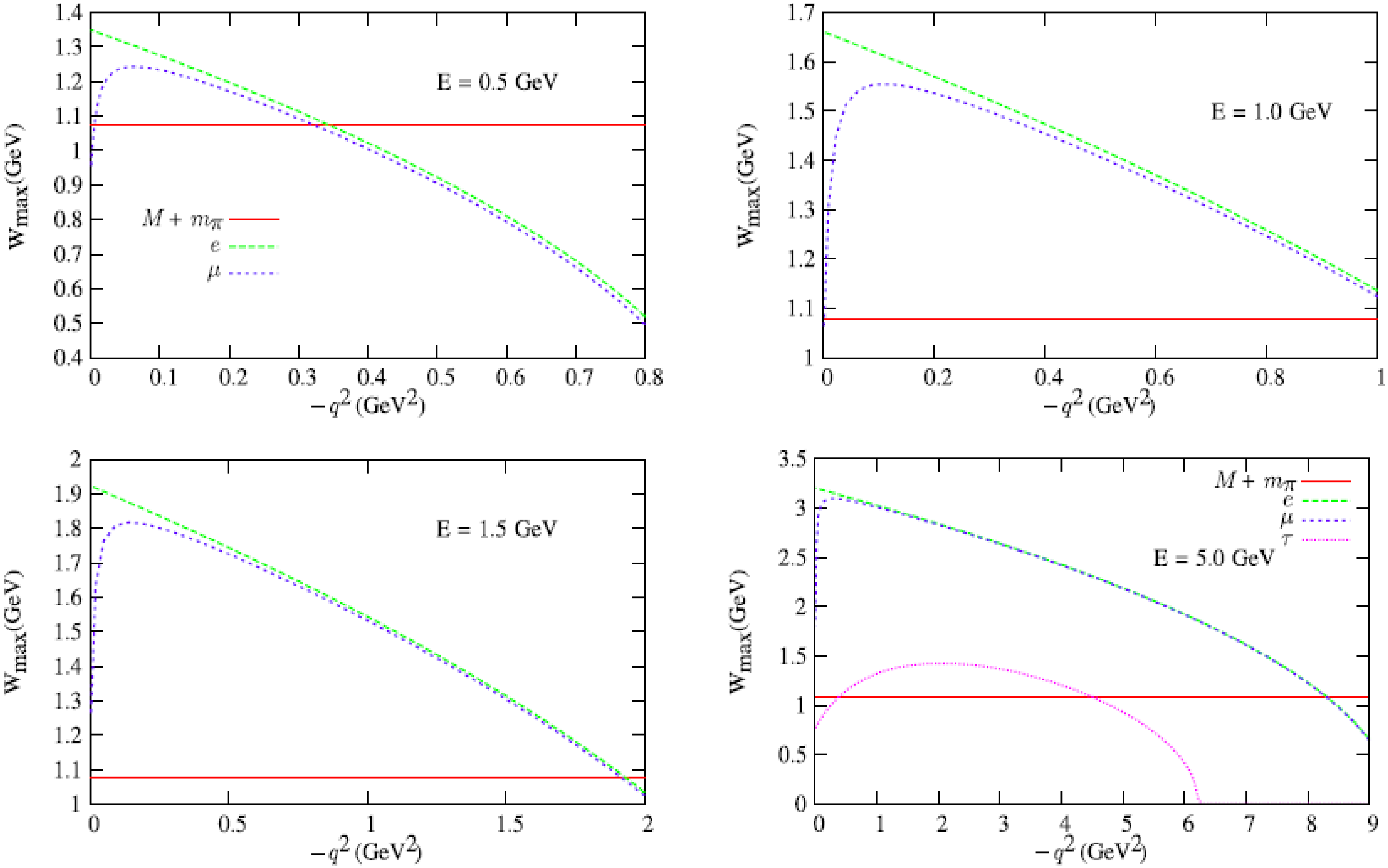
$$\mathcal{L}_{\Delta,N,\mathrm{bg}} = \frac{ic_{1\Delta}}{M}\overline{\Delta}^{a}_{\mu}\gamma_{\nu}\gamma^{5}T^{\dagger iA}_{a}F^{(+)\mu\nu}_{i}N_{A} + \frac{ic_{3\Delta}}{M^{2}}\overline{\Delta}^{a}_{\mu}i\gamma^{5}T^{\dagger iA}_{a}(\widetilde{\partial}_{\nu}F^{(+)\mu\nu})_{i}N_{A} + \frac{c_{6\Delta}}{M^{2}}\overline{\Delta}^{a}_{\lambda}\sigma_{\mu\nu}T^{\dagger iA}_{a}(\widetilde{\partial}^{\lambda}\overline{F}^{(+)\mu\nu})_{i}N_{A}$$

$$- \frac{d_{2\Delta}}{M^{2}}\overline{\Delta}^{a}_{\mu}T^{\dagger iA}_{a}(\widetilde{\partial}_{\nu}F^{(-)\mu\nu})_{i}N_{A} - \frac{id_{4\Delta}}{M}\overline{\Delta}^{a}_{\mu}\gamma_{\nu}T^{\dagger iA}_{a}F^{(-)\mu\nu}_{i}N_{A} - \frac{id_{7\Delta}}{M^{2}}\overline{\Delta}^{a}_{\lambda}\sigma_{\mu\nu}T^{\dagger iA}_{a}(\widetilde{\partial}^{\lambda}F^{(-)\mu\nu})_{i}N_{A} + \mathrm{c.c.},$$

$$\mathcal{L}_{\Delta,N,\rho} = \frac{ic_{1\Delta\rho}}{M}\overline{\Delta}^{a}_{\mu}\gamma_{\nu}\gamma^{5}T^{\dagger iA}_{a}\rho^{\mu\nu}_{i}N_{A} + \frac{ic_{3\Delta\rho}}{M^{2}}\overline{\Delta}^{a}_{\mu}i\gamma^{5}T^{\dagger iA}_{a}(\widetilde{\partial}_{\nu}\rho^{\mu\nu})_{i}N_{A} + \frac{c_{6\Delta\rho}}{M^{2}}\overline{\Delta}^{a}_{\lambda}\sigma_{\mu\nu}T^{\dagger iA}_{a}(\widetilde{\partial}^{\lambda}\overline{\rho}^{\mu\nu})_{i}N_{A} + \mathrm{c.c.}.$$

A quick look (recap)

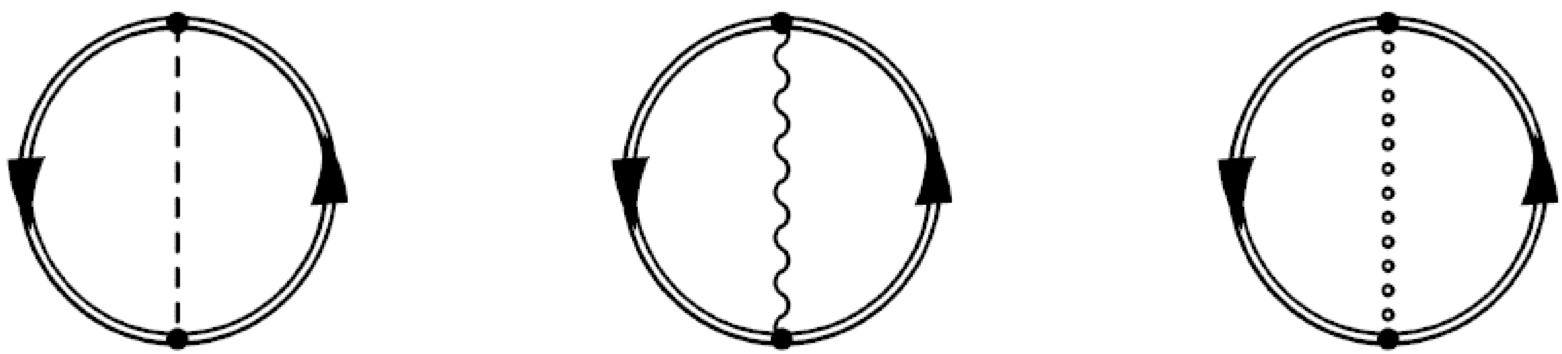
- Chiral symmetry
- The lagrangian
- Electroweak interactions (CVC and PCAC)
- Two-body currents



*E. Herna´ndez, J. Nieves, and M. Valverde, Phys. Rev. D **76,** 033005 (2007)*

Where Are the Pions?

- For nuclear equation of state (EOS), 1- and 2-loop calculations (including pion) are done by Y. Hu, J. McIntire, and B. Serot (NPA 794:187, 2007); Infrared Regularization.



Spin-3/2 Particle in EFT

- Redundant degrees of freedom in Rarita-Schwinger representation (ψ^μ) do NOT show up.

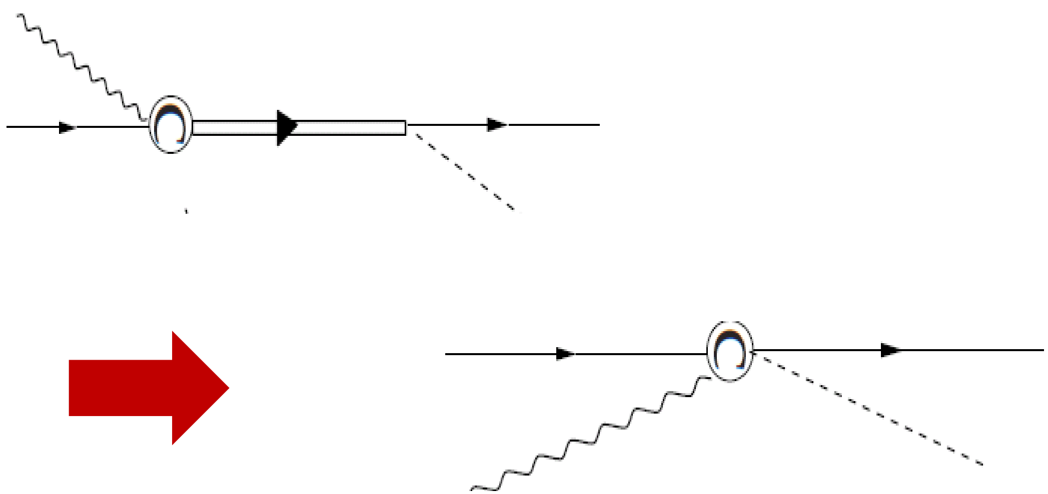
$$
\begin{aligned}
S_F &= (S_F^{0(\frac{3}{2})} + S_F^{0(\frac{3}{2}\perp)}) + (S_F^{0(\frac{3}{2})} + S_F^{0(\frac{3}{2}\perp)})(\Sigma^{(\frac{3}{2})} + \Sigma^{(\frac{3}{2}\perp)})(S_F^{0(\frac{3}{2})} + S_F^{0(\frac{3}{2}\perp)}) + \cdots \\
&= S_F^{0(\frac{3}{2})} + S_F^{0(\frac{3}{2})}\Sigma^{(\frac{3}{2})}S_F^{0(\frac{3}{2})} + \cdots \\
&\quad + S_F^{0(\frac{3}{2}\perp)} + S_F^{0(\frac{3}{2}\perp)}\Sigma^{(\frac{3}{2}\perp)}S_F^{0(\frac{3}{2}\perp)} + \cdots
\end{aligned}
$$

This can be generalized to other spins

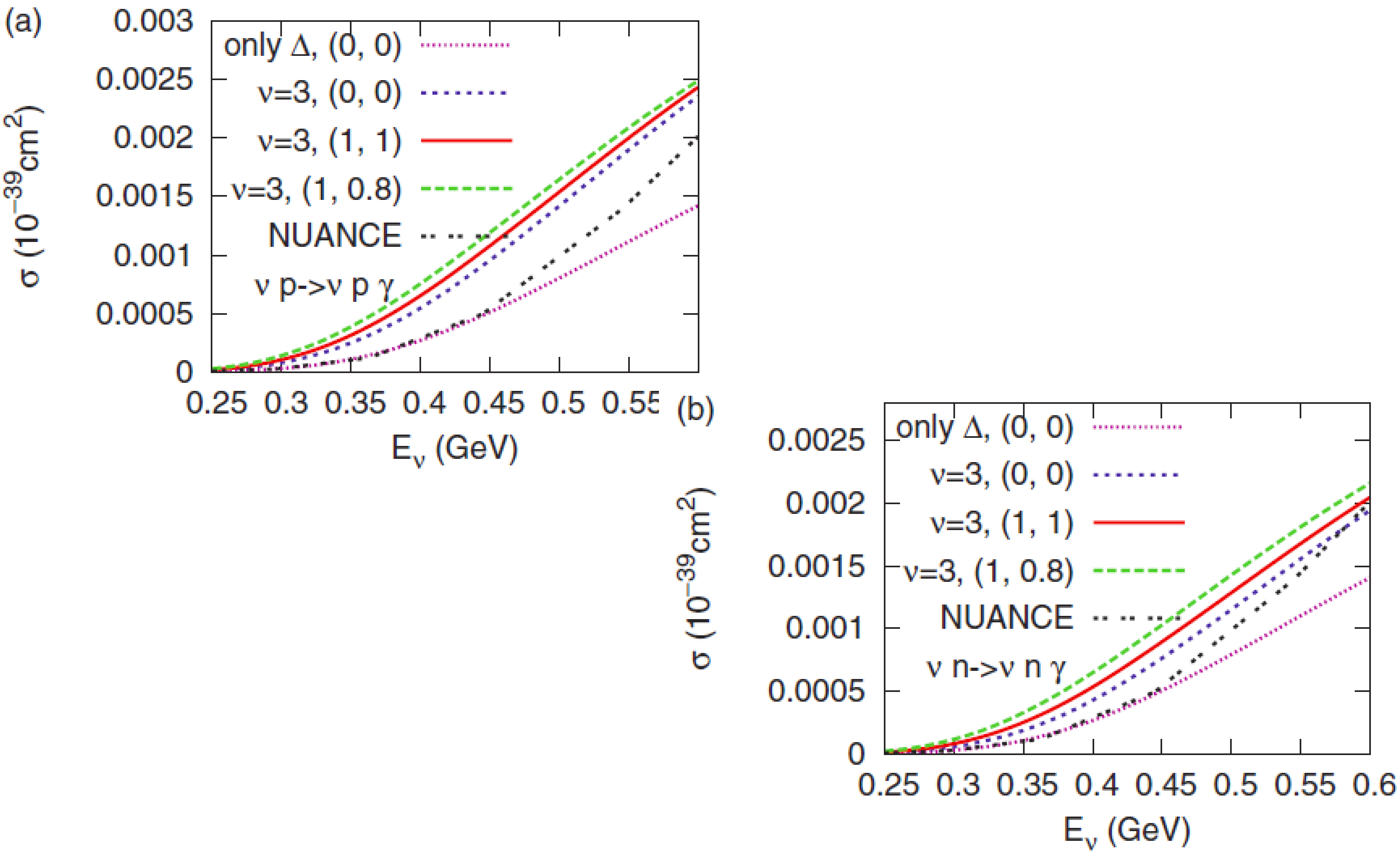
Related work: V. Pascalutsa, PRD 58: 096002, 1998; V. P and D. Phillips, PRC 67: 055202, 2003; H. Krebs, E. Epelbaum, and U. Meissner, PRC 80: 028201, 2009; PLB 683: 222, 2010

Spin-3/2 Particle in EFT

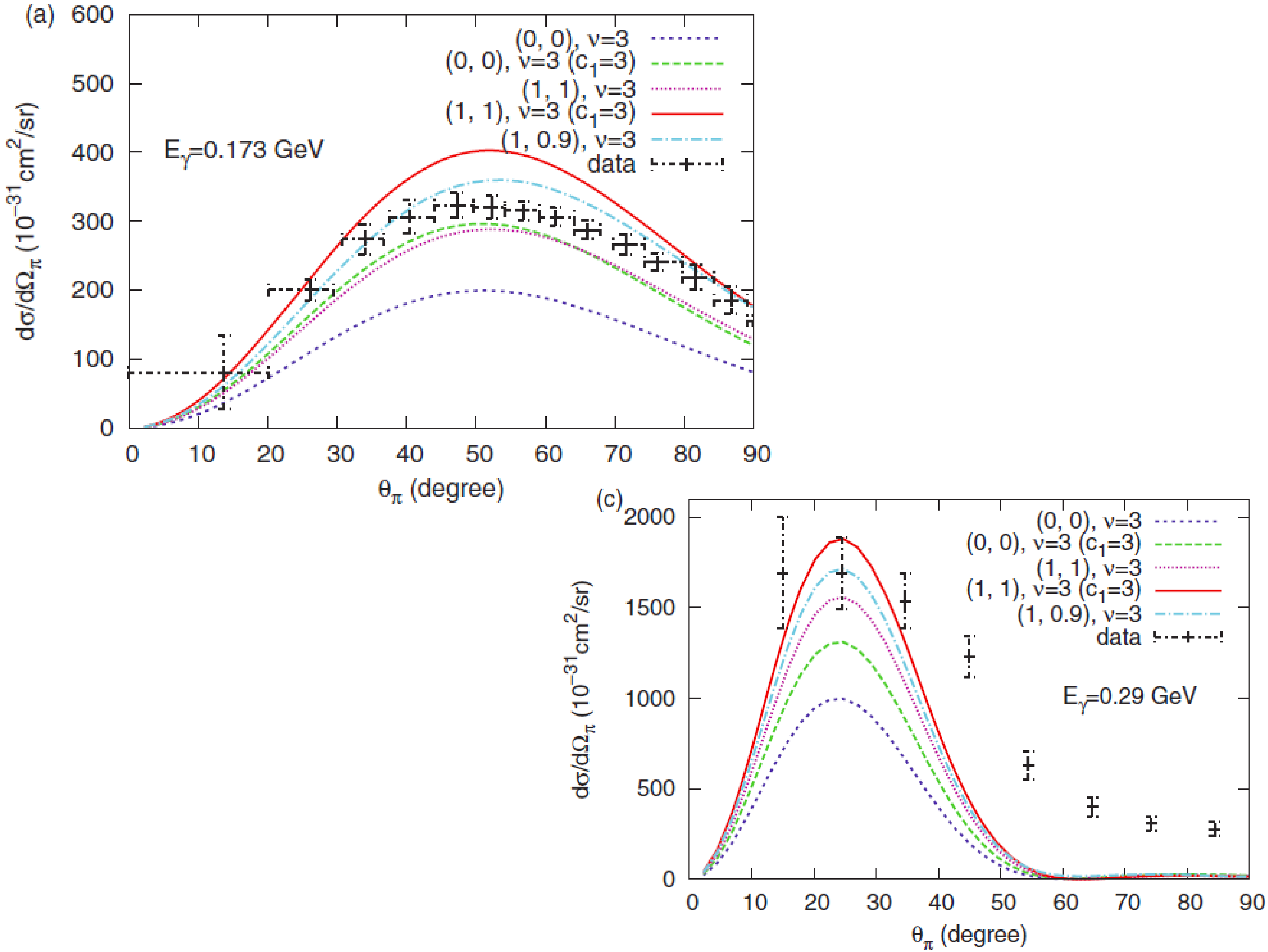
- Redundant degrees of freedom in Rarita-Schwinger representation (ψ^μ) do NOT show up.
- Off-shell couplings: $\gamma_\mu\psi^\mu$, $\partial_\mu\psi^\mu$, $\overline{\psi}^\mu\gamma_\mu$, and $\partial_\mu\overline{\psi}^\mu$



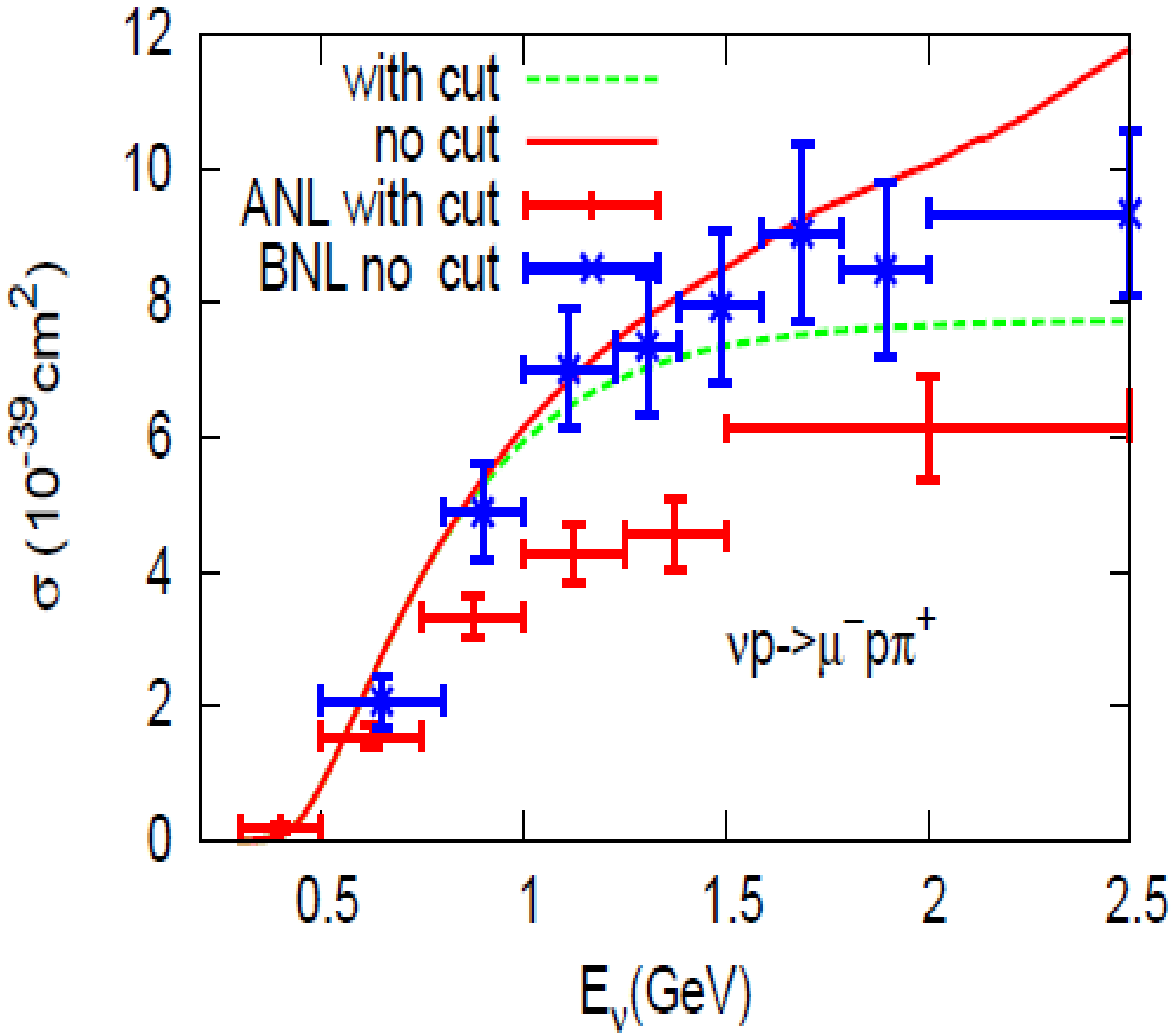
NC photon



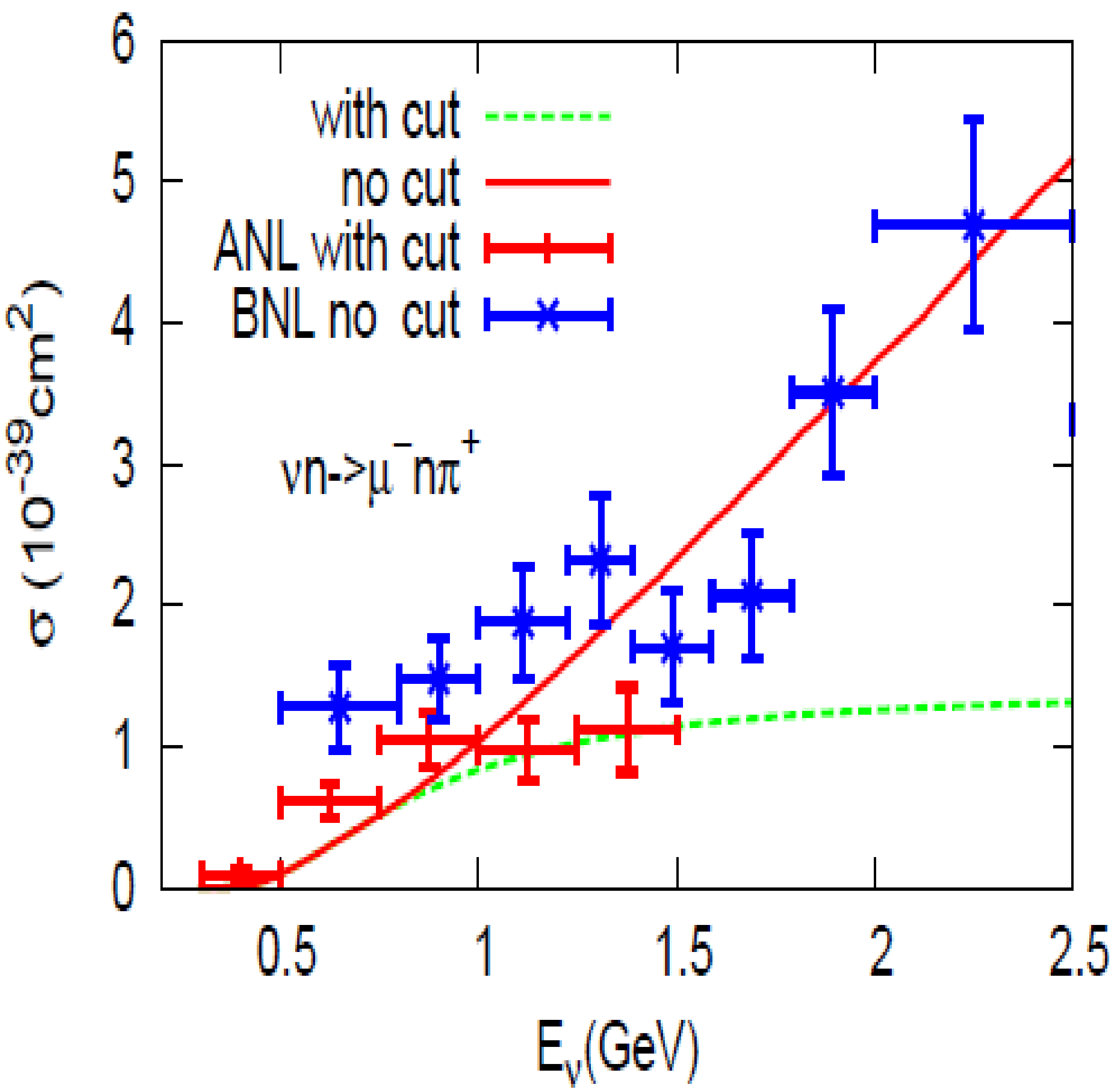
(a)
only Δ, (0, 0)
ν=3, (0, 0)
ν=3, (1, 1)
ν=3, (1, 0.8)
NUANCE
ν p->ν p γ
σ (10^-39cm^2)
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
0.25 0.3 0.35 0.4 0.45 0.5 0.55
E_ν (GeV)
(b)
only Δ, (0, 0)
ν=3, (0, 0)
ν=3, (1, 1)
ν=3, (1, 0.8)
NUANCE
ν n->ν n γ
σ (10^-39cm^2)
0.0025
0.002
0.0015
0.001
0.0005
0
0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6
E_ν (GeV)


(a)
E$_\gamma$=0.173 GeV
(0, 0), ν=3
(0, 0), ν=3 (c$_1$=3)
(1, 1), ν=3
(1, 1), ν=3 (c$_1$=3)
(1, 0.9), ν=3
data
dσ/dΩ$_\pi$ (10^{-31}cm^2/sr)
θ$_\pi$ (degree)
(c)
E$_\gamma$=0.29 GeV
(0, 0), ν=3
(0, 0), ν=3 (c$_1$=3)
(1, 1), ν=3
(1, 1), ν=3 (c$_1$=3)
(1, 0.9), ν=3
data
dσ/dΩ$_\pi$ (10^{-31}cm^2/sr)
θ$_\pi$ (degree)

Benchmarks

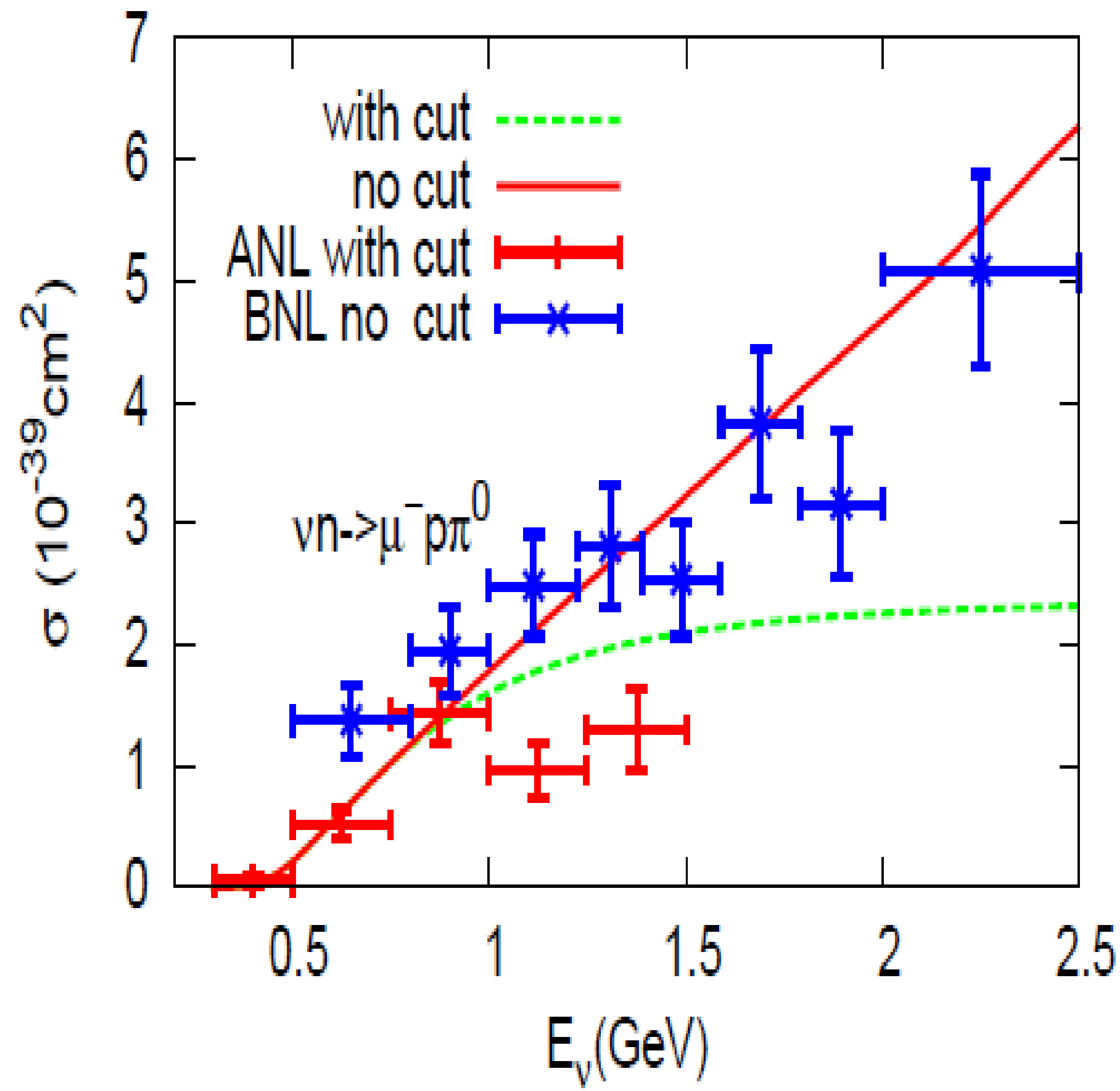

with cut
no cut
ANL with cut
BNL no cut
νp->μ⁻pπ⁺
σ (10⁻³⁹cm²)
E_ν(GeV)
0
2
4
6
8
10
12
0.5
1
1.5
2
2.5

Benchmarks



6
5
4
3
2
1
0
0.5
1
1.5
2
2.5
σ (10^-39 cm^2)
E_ν(GeV)
with cut
no cut
ANL with cut
BNL no cut
νn->μ⁻nπ⁺

Benchmarks



with cut
no cut
ANL with cut
BNL no cut
νn->μ⁻pπ⁰
σ (10⁻³⁹cm²)
E_ν(GeV)
0
1
2
3
4
5
6
7
0.5
1
1.5
2
2.5