(Electroweak) Pion and photon emission in a (chiral) effective field theory for nuclei (and beyond)

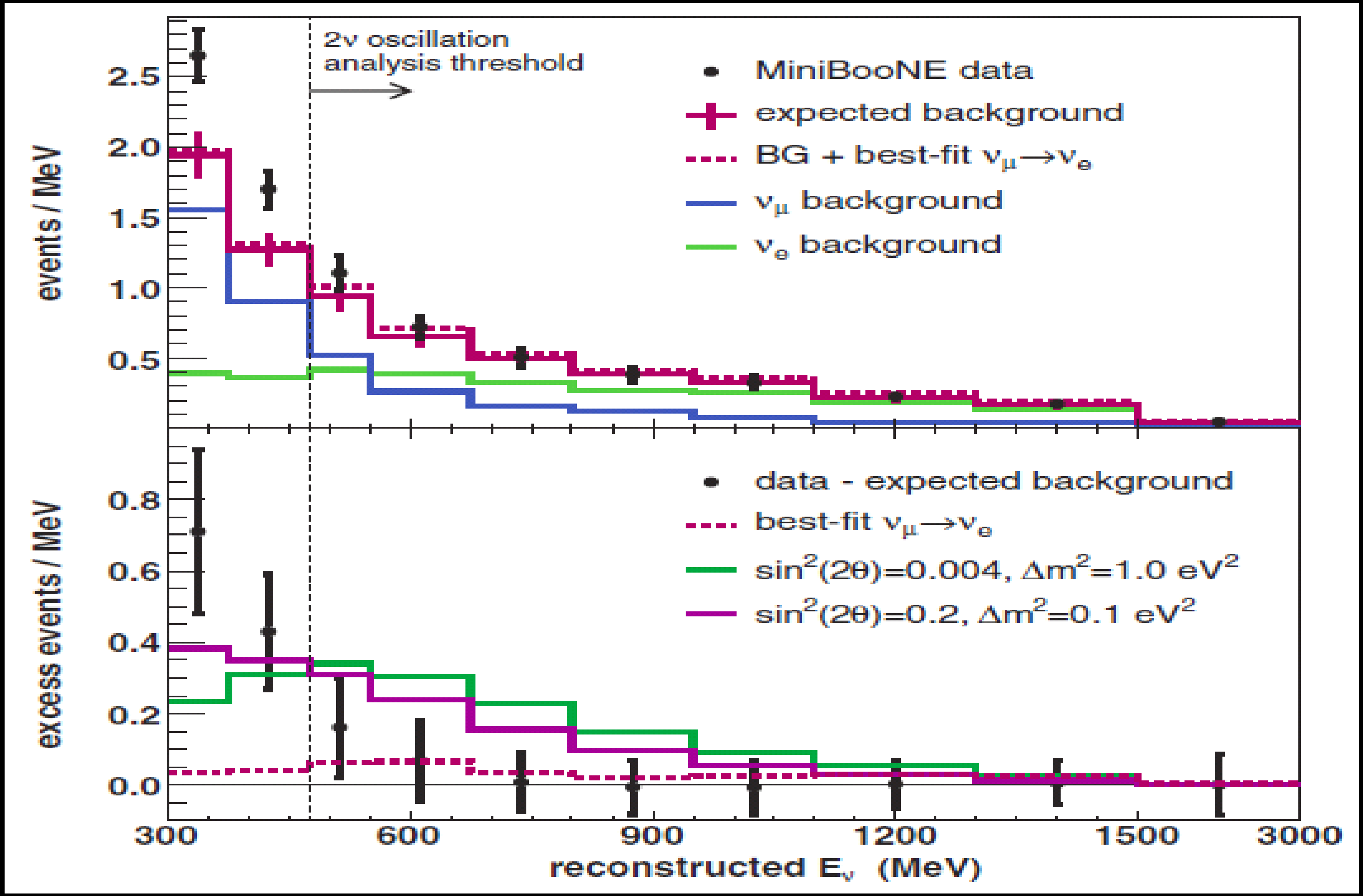
Xilin Zhang (with Brian Serot at Indiana U.),
Institute of nuclear and particle physics, Ohio U.

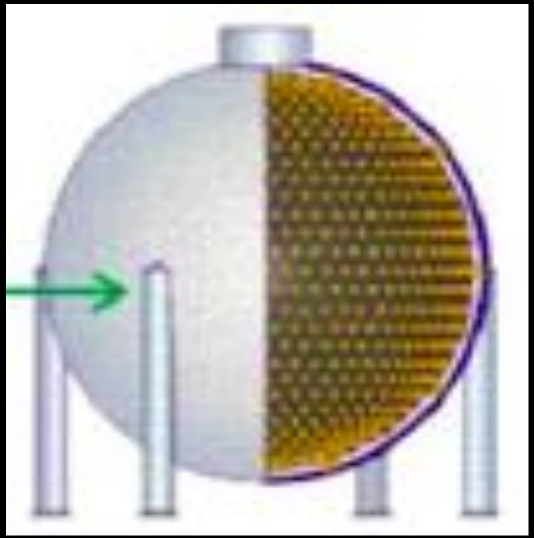
For NuFact 2013 at IHEP, Beijing, China

Outline

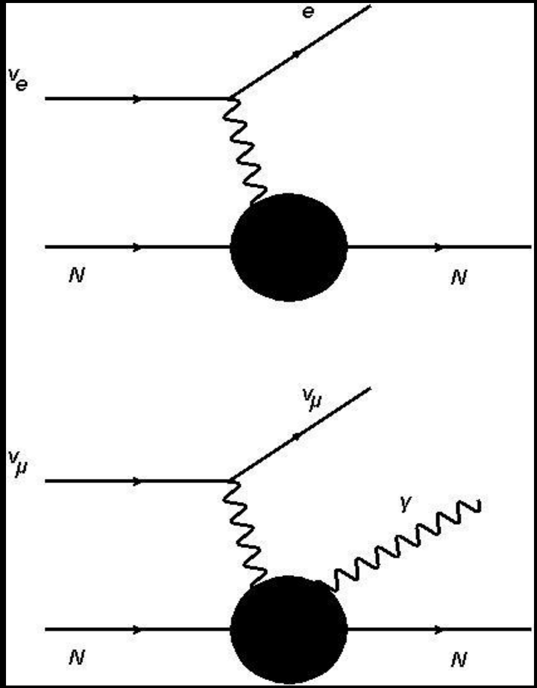
- Motivation: MiniBooNE low energy excess
- QHD EFT frame work: a quick but important introduction
- Pion and photon neutrinoproduction from nucleon
- Incoherent and coherent productions from nucleus, reaction kernel modification (s channel) in the medium
- MiniBooNE neutral current (NC) photon production and excess events: a short report
- Summary

MiniBooNE



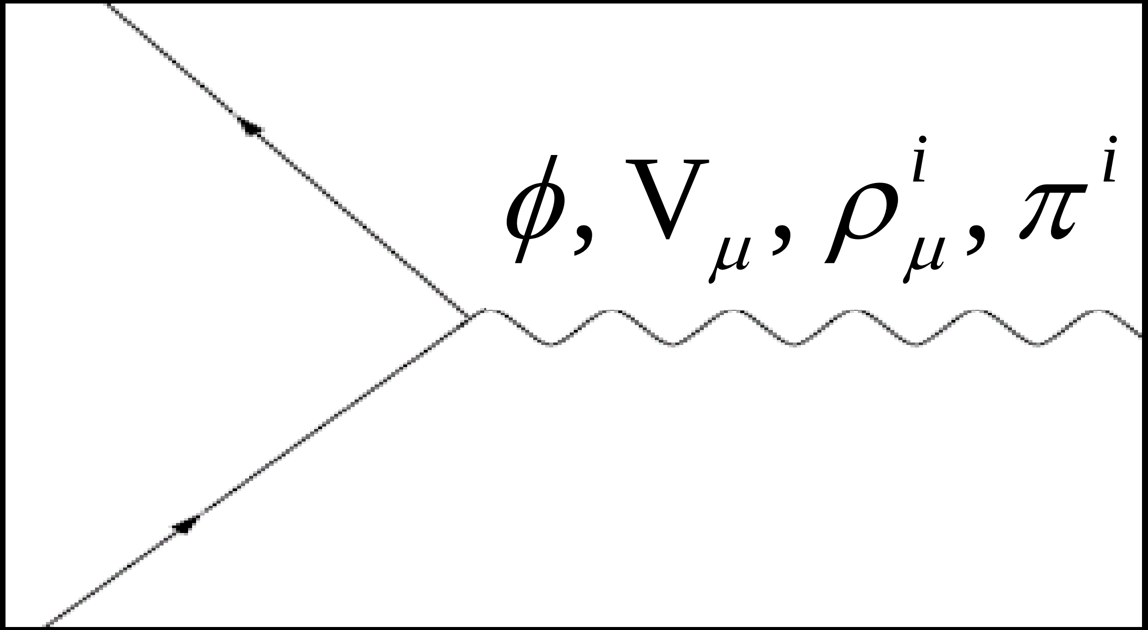


800 tons mineral oil (CH2)



Introduction to quantum hadrondynamics effective field theory (QHD EFT)

- NN interactions (relativistic field theory since 1970):



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

Intro. to QHD

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

Beyond (local) Fermi gas (LFG)

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

Intro. to QHD

- NN interactions (relativistic field theory)
- Mean-field approximation (RMF): for nuclear matter and mid--heavy nuclei; boson fields develop expectation values; nucleon spin-orbital coupling…
- Symmetries: $SU(2)_L \otimes SU(2)_R \otimes U(1)_B$
  - Lorentz; C, P, T, and the breakings
  - Chiral symmetry and it's spontaneous breaking→ isospin symmetry; pion dynamics; and **electroweak currents (CVC and PCAC)**

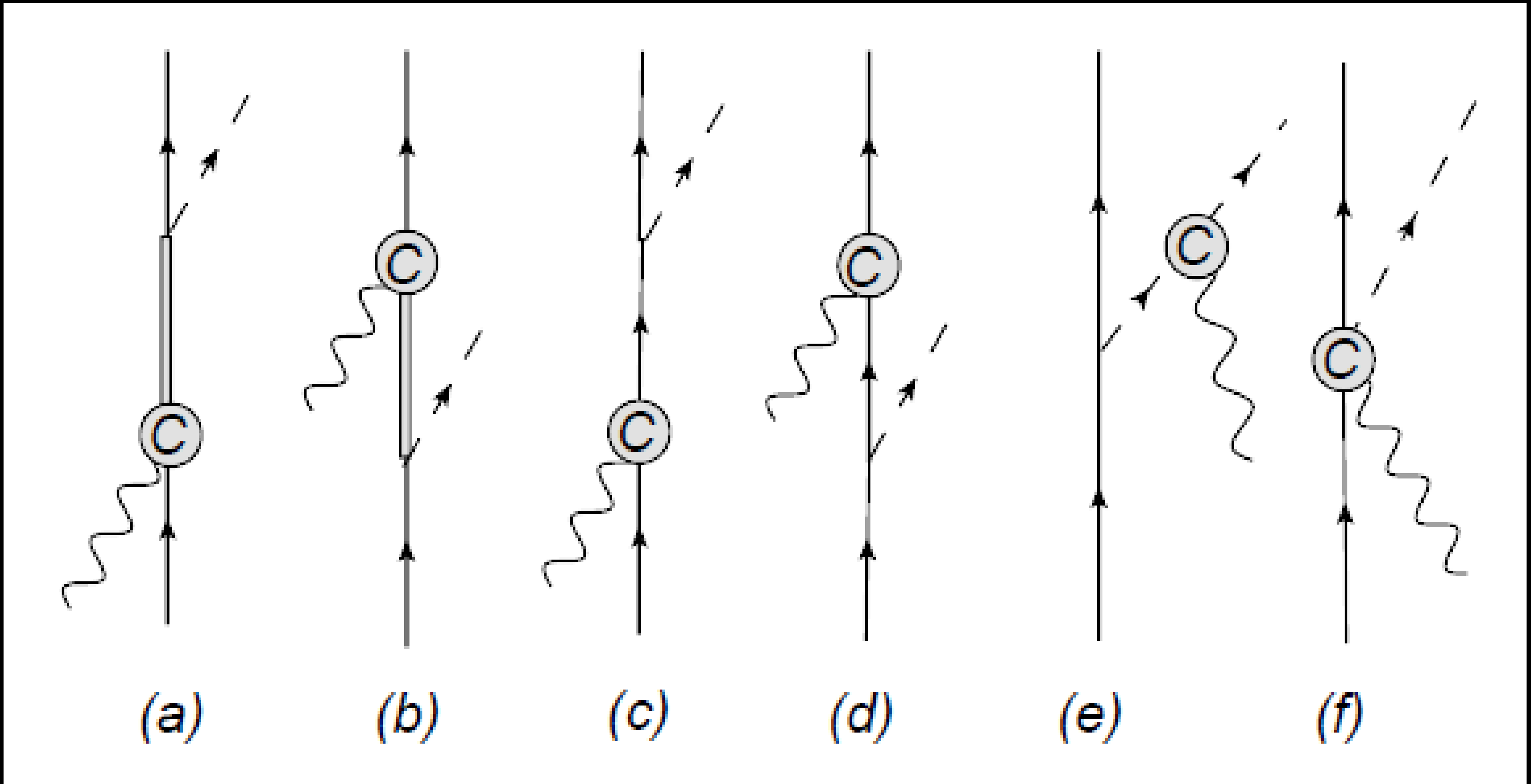
B. Serot and X.Z., arXiv:1011.5913; Advances in QFT (InTech, 2012) (arXiv:1110.2760)

Intro. to QHD

- NN interactions (relativistic field theory)
- Mean-field approximation (RMF)
- Symmetries
- QHD can be used to study hadron behavior in medium: Delta modification; pion and nucleon optical potentials. A new development of loop calculations in QHD EFT.

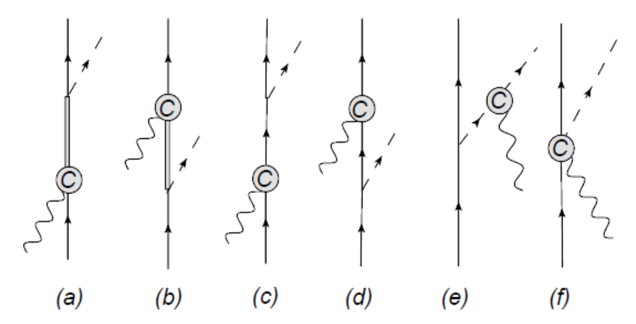
Y. Hu, J. McIntire, and B. Serot (NPA 794:187, 2007)

Calibration at nucleon level: pion production



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

Current form factors



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

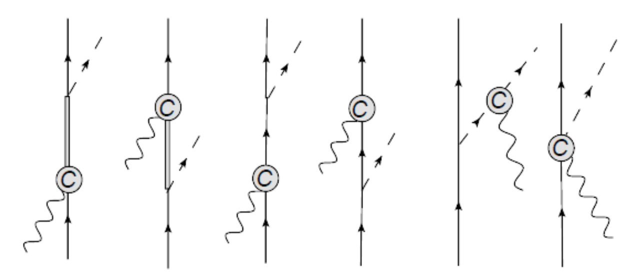
$$\begin{aligned}\langle N,B;\pi,j,k_\pi|A_\mu^i|N,A\rangle = & -\frac{\epsilon^i{}_{jk}}{f_\pi}\langle B|\frac{\tau^k}{2}|A\rangle \bar{u}_f \gamma^\nu u_i \left[g_{\mu\nu} + 2\delta F_1^{V,md}((q-k_\pi)^2)\frac{q\cdot(q-k_\pi)g_{\mu\nu} - (q-k_\pi)_\mu q_\nu}{(q-k_\pi)^2}\right] \\ & -\frac{\epsilon^i{}_{jk}}{f_\pi}\langle B|\frac{\tau^k}{2}|A\rangle \bar{u}_f \frac{\sigma_{\mu\nu} i q^\nu}{2M} u_i \left[2\lambda^{(1)} + 2\delta F_2^{V,md}((q-k_\pi)^2)\frac{q\cdot(q-k_\pi)}{(q-k_\pi)^2}\right] \\ & \equiv \frac{\epsilon^i{}_{jk}}{f_\pi}\langle B|\frac{\tau^k}{2}|A\rangle \bar{u}_f \Gamma_{A\pi\mu}(q,k_\pi) u_i.\end{aligned}$$

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

$$F_2^{V,md} = \frac{1}{2}\left(2\lambda^{(1)} - \frac{f_\rho g_\rho}{g_\gamma}\frac{q^2}{q^2 - m_\rho^2}\right)$$

VMD. This relation will be used in high energy extrapolation.

Current form factors



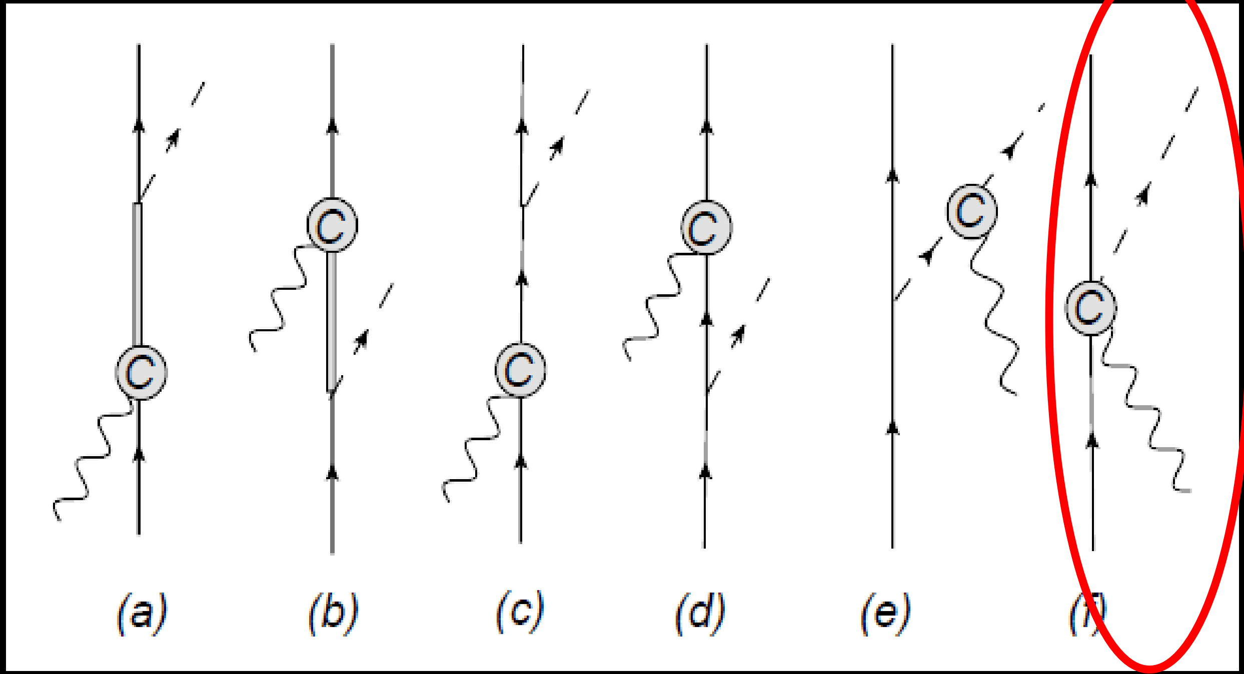
$$\langle \Delta, a, p_\Delta | V^{i\mu}(A^{i\mu}) | N, A, p_N \rangle \equiv T_a^{\dagger\, iA}\, \overline{u}_{\Delta\alpha}(p_\Delta)\, \Gamma^{\alpha\mu}_{V(A)}(q)\, u_N(p_N)$$

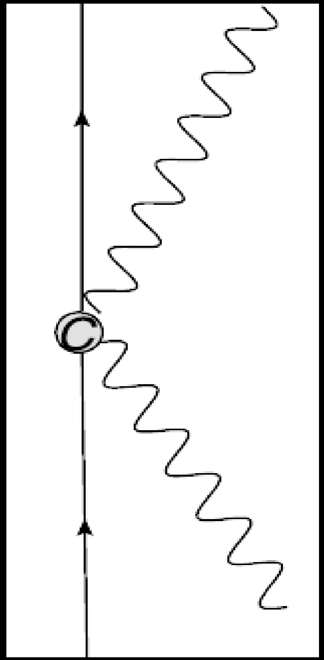
$$\Gamma^{\alpha\mu}_A = -h_A \left(g^{\alpha\mu} - \frac{q^\alpha q^\mu}{q^2 - m_\pi^2} \right) + \frac{2d_{2\Delta}}{M^2}\left(q^\alpha q^\mu - g^{\alpha\mu} q^2\right) - \frac{2d_{4\Delta}}{M}\left(q^\alpha \gamma^\mu - g^{\alpha\mu} \not{q}\right) - \frac{4d_{7\Delta}}{M^2} q^\alpha \sigma^{\mu\nu}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

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

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

Calibration at nucleon level: NC photon prod.



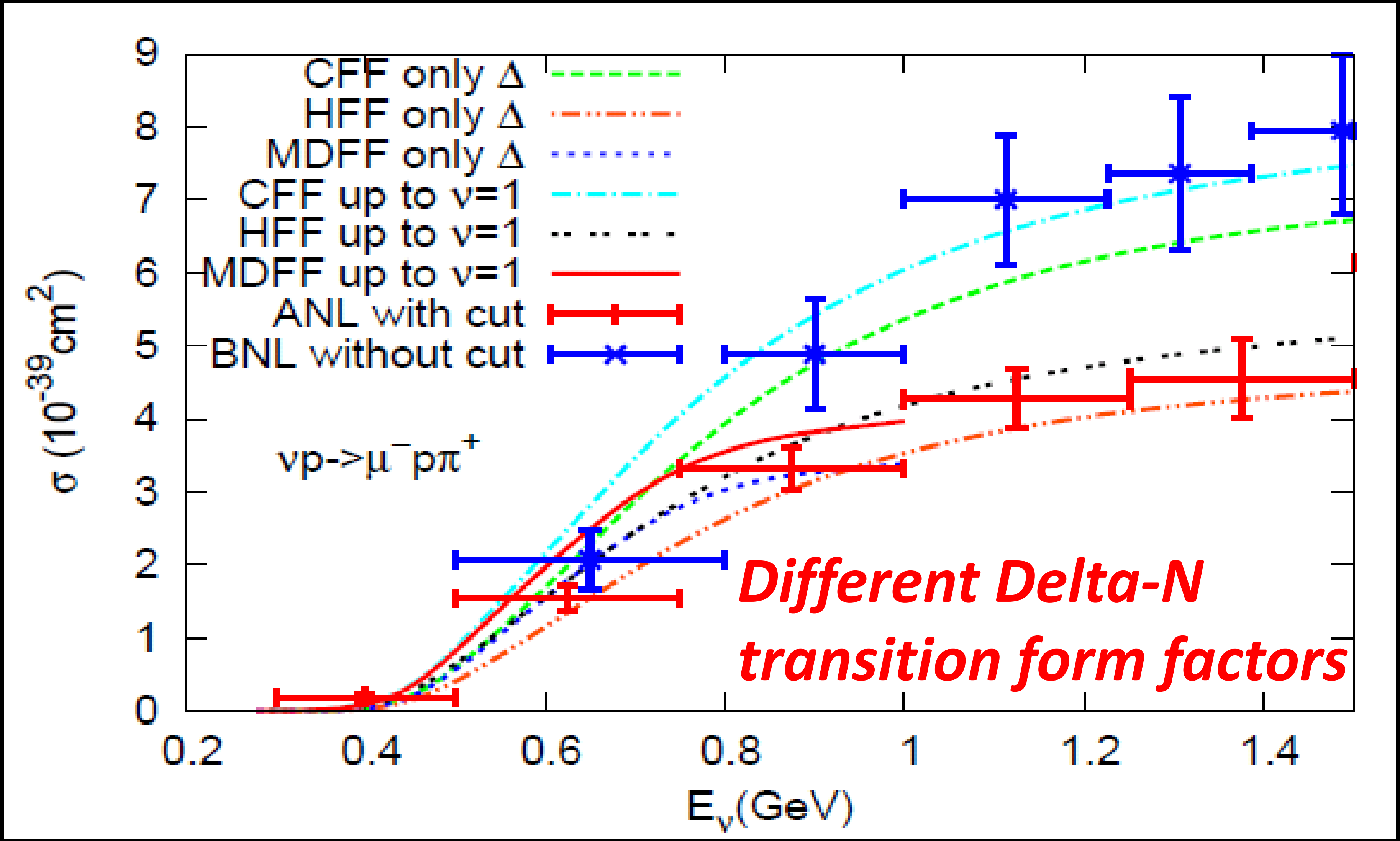


Results?

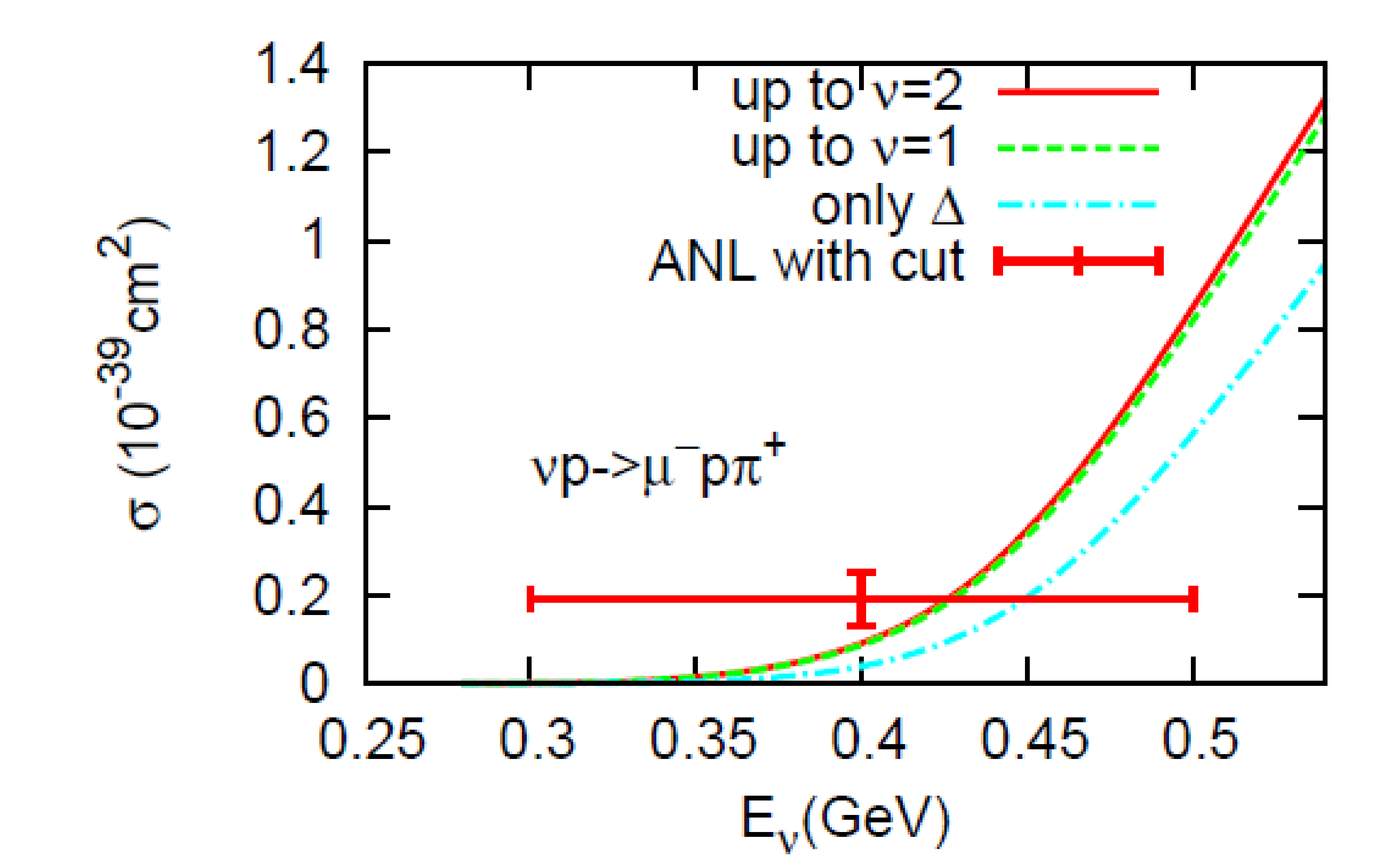
$$\frac{c_1}{M^2}\overline{N}\gamma^\mu N\,\mathrm{Tr}(\widetilde{a}^\nu \overline{F}^{(+)}_{\mu\nu}), \qquad \frac{e_1}{M^2}\overline{N}\gamma^\mu \widetilde{a}^\nu N \overline{f}_{s\mu\nu}$$

Already in the previous lagrangian. Also related to electro(photo) pion prod.

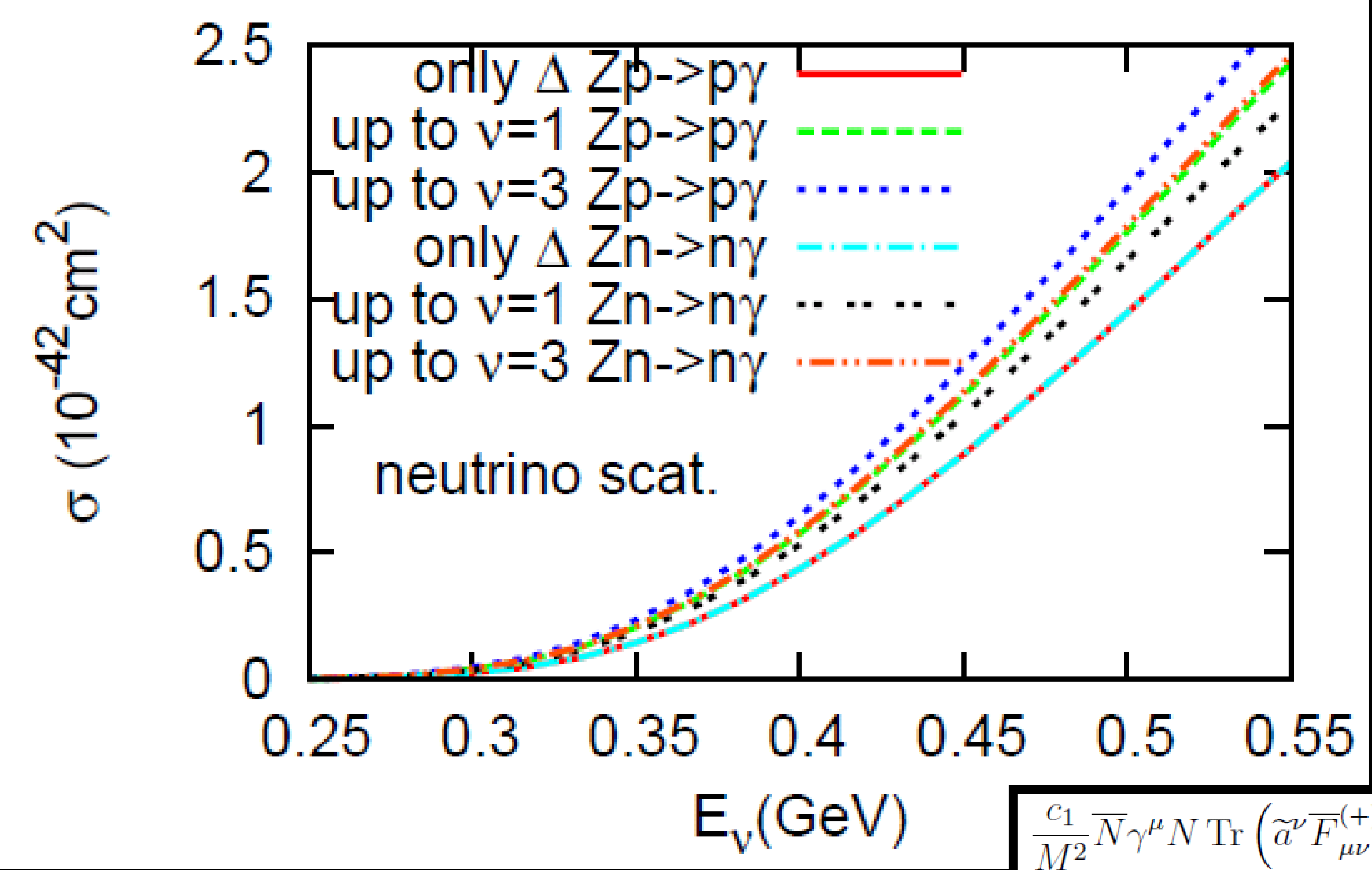
*R. J. Hill, Phys. Rev. D **81**, 013008 (2010)*



*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).*



Power counting of the calculation



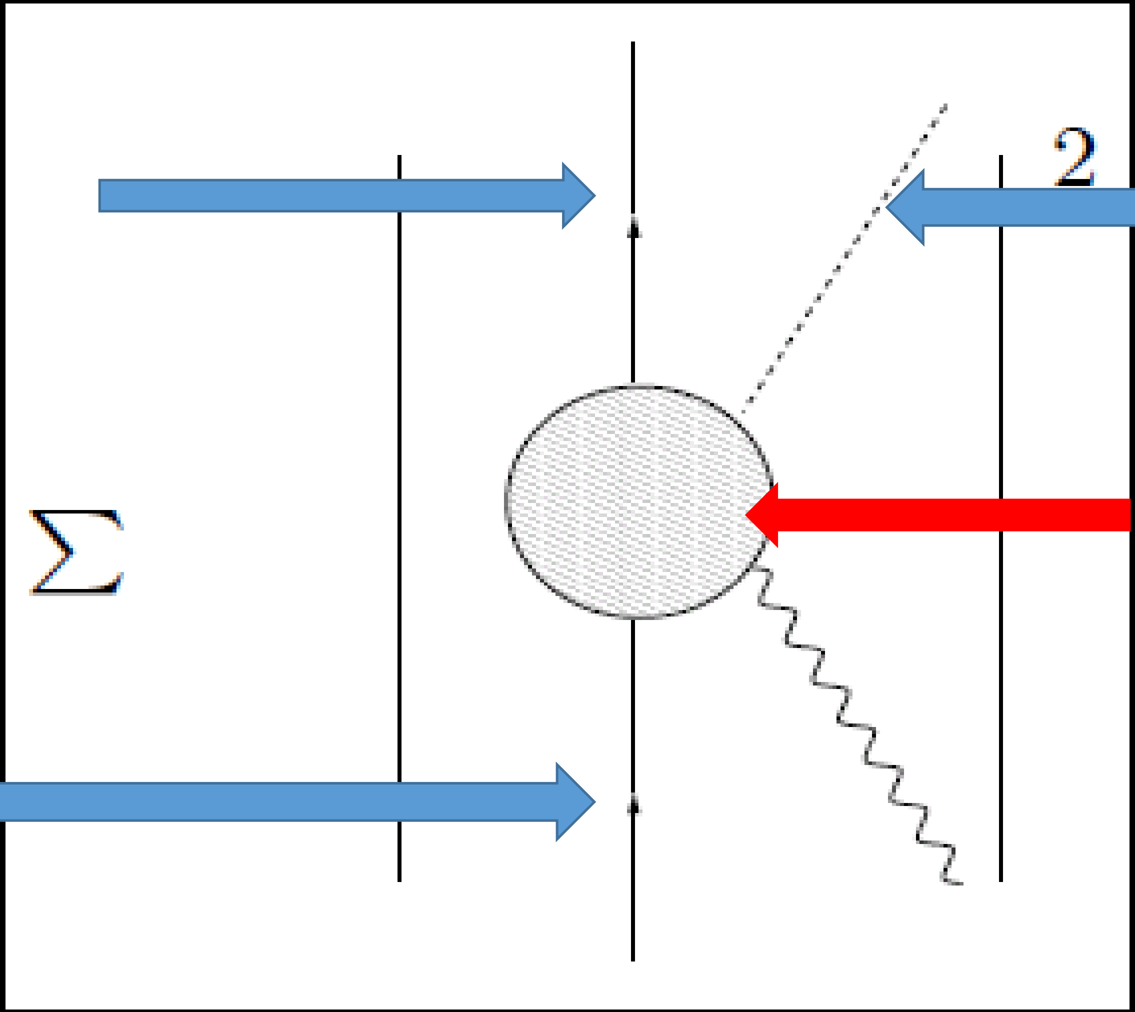
$$\frac{c_1}{M^2}\overline{N}\gamma^\mu N\,\mathrm{Tr}\left(\widetilde{a}^\nu \overline{F}^{(+)}_{\mu\nu}\right) \; ,$$

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

Incoherent pion and photon production from Nucleus

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

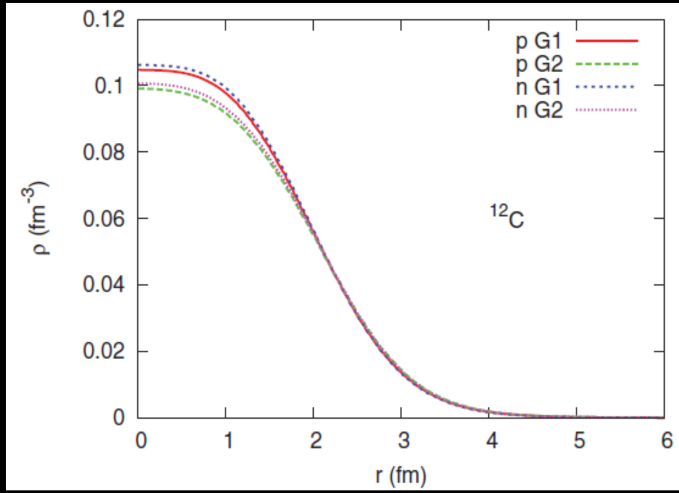
Initial nucleon (shell) wave function

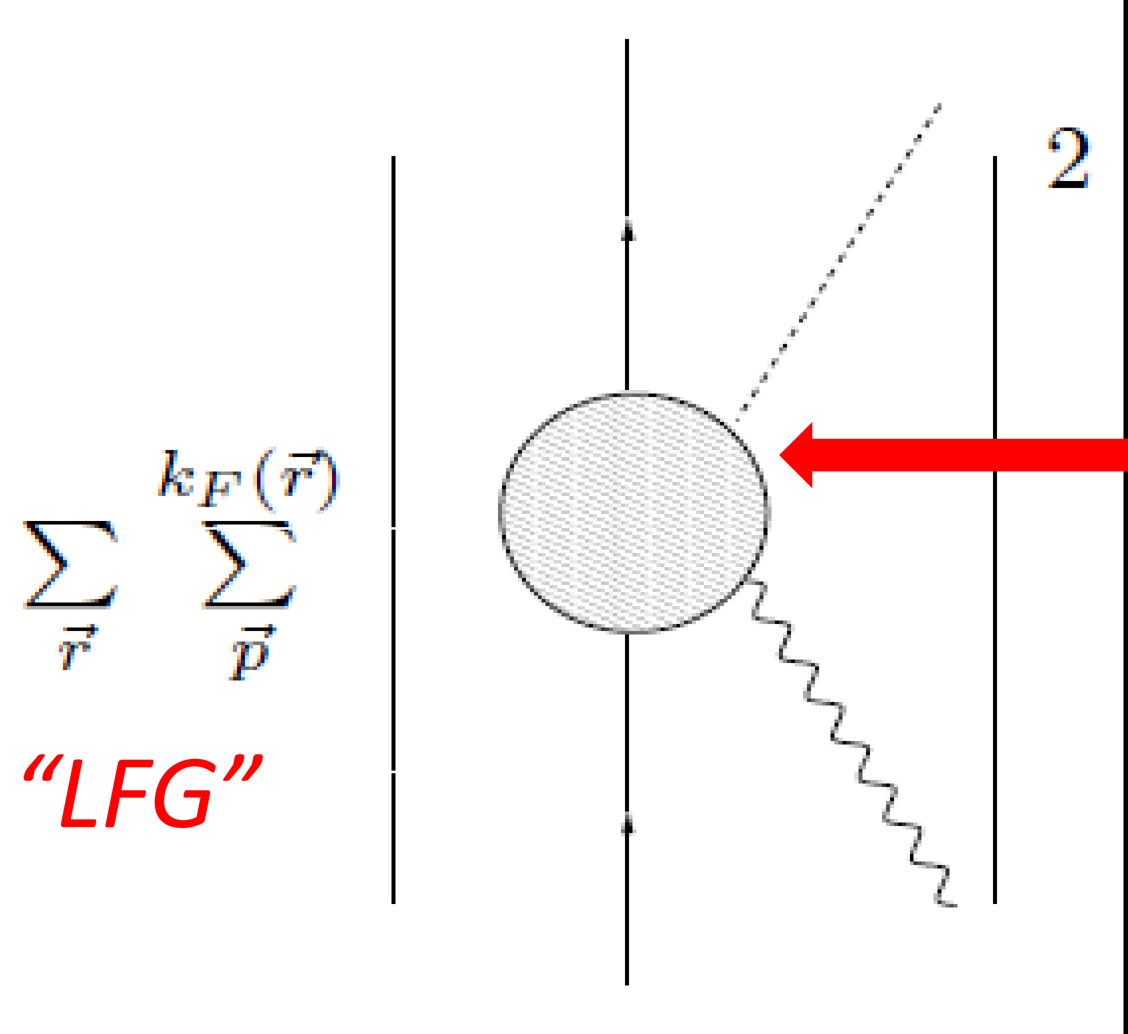


Pion FSI, optical potential

Medium modification of intermediate states: Delta

Incoherent pion and photon production from Nucleus





"LFG"

Medium modification of intermediate states: Delta

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

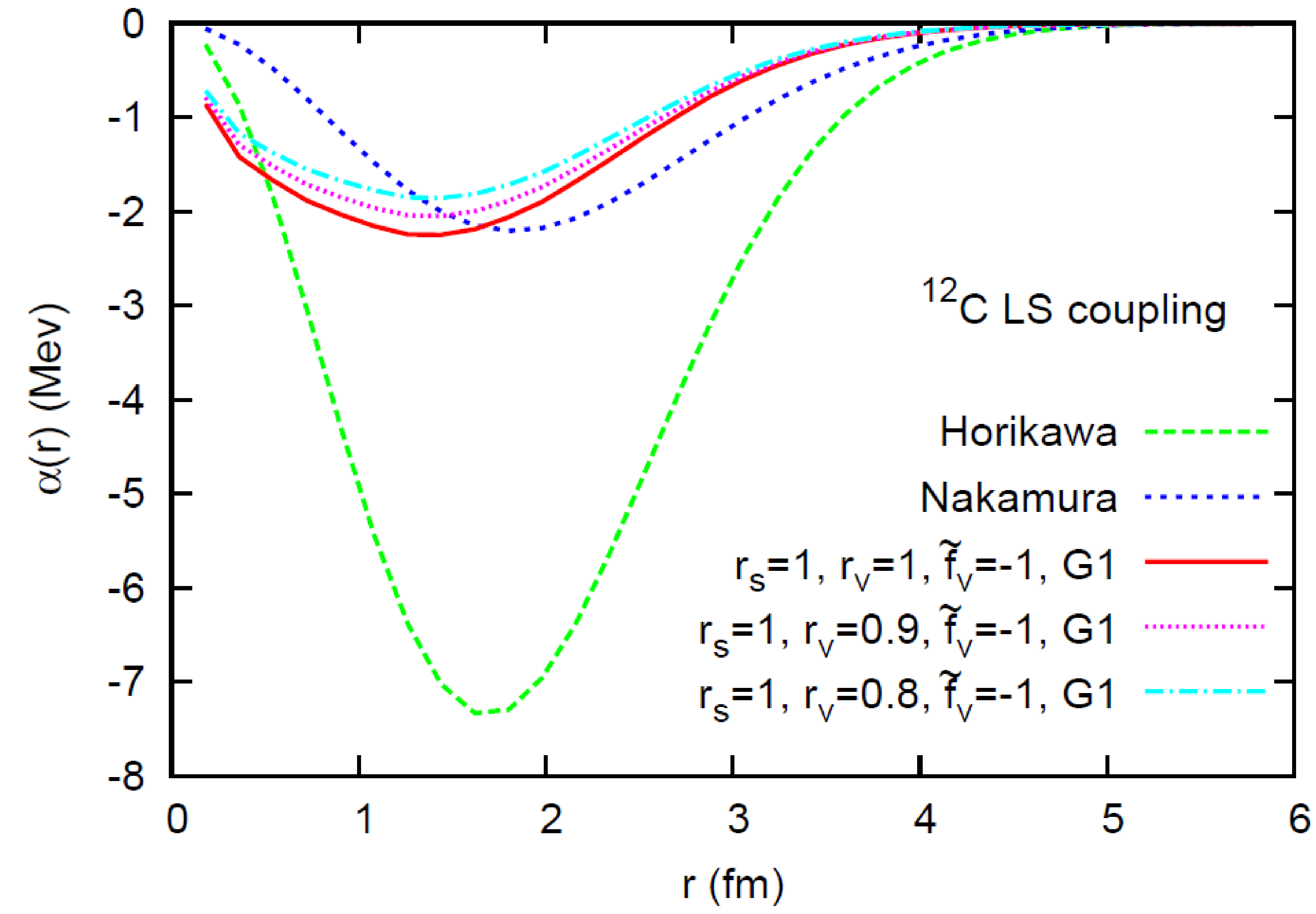
Delta dynamics in nuclear medium

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

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

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

$$\begin{aligned} h_\Delta &= \frac{1}{3}\left[\frac{1}{2\overline{m}^2\ r}\frac{d}{dr}\left(h_s\langle\phi\rangle + h_v\langle V^0\rangle\right) - \frac{\widetilde{f}_v}{m\overline{m}\ r}\frac{d}{dr}\left(h_v\langle V^0\rangle\right)\right]\vec{S}\cdot\vec{L} \\ &\equiv \alpha(r)\vec{S}\cdot\vec{L}\ . \end{aligned}$$



Y. Horikawa, M. Thies, and F. Lenz, NPA ***345****, 386 (1980).*

S. X. Nakamura, T. Sato, T.-S. H. Lee, B. Szczerbinska, and K. Kubodera, PRC ***81****, 035502 (2010).*

Delta dynamics in nuclear medium

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

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

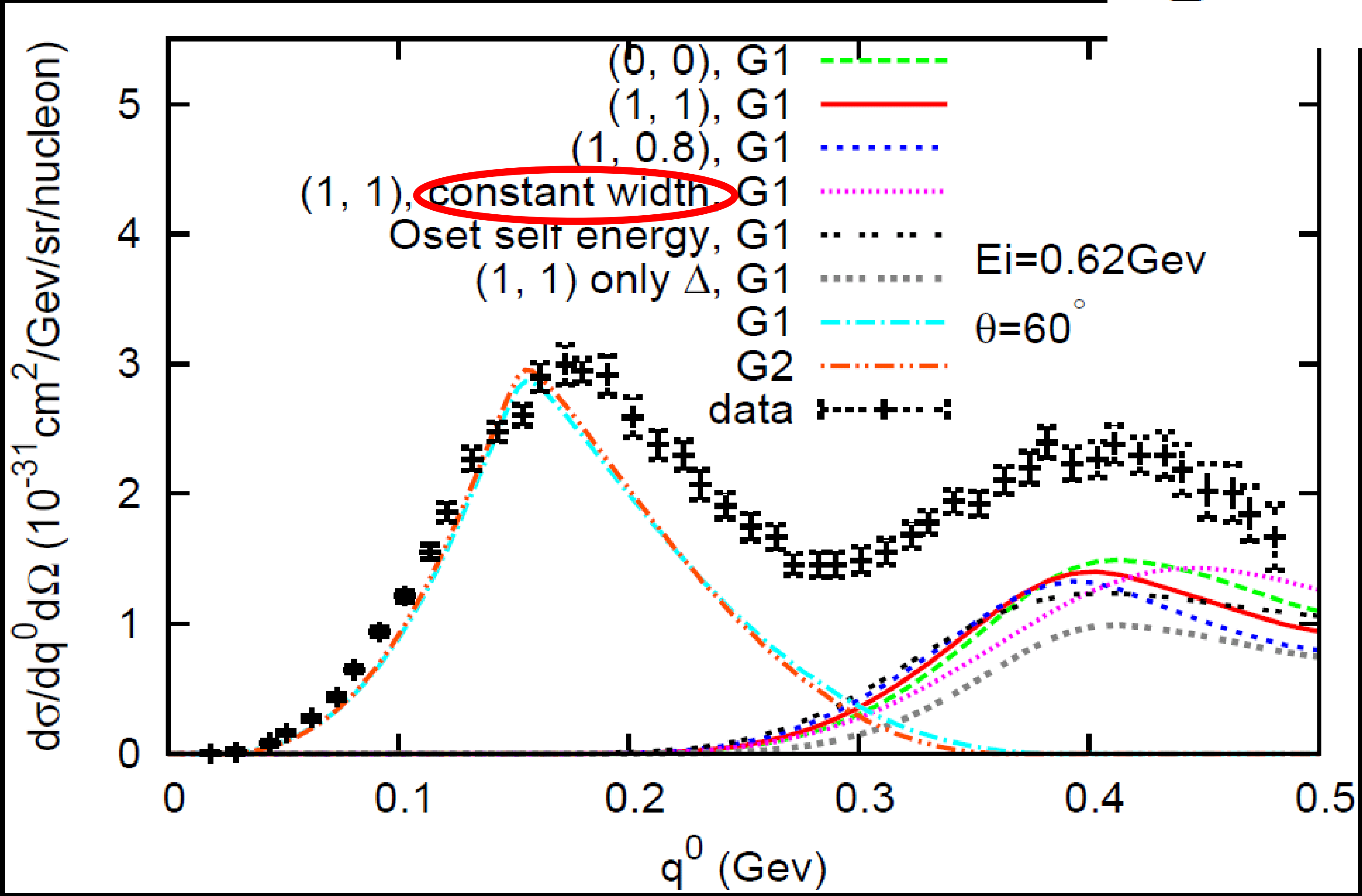
$$\Gamma_{sp} = V_0 \times \frac{\rho(r)}{\rho(0)}$$

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

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

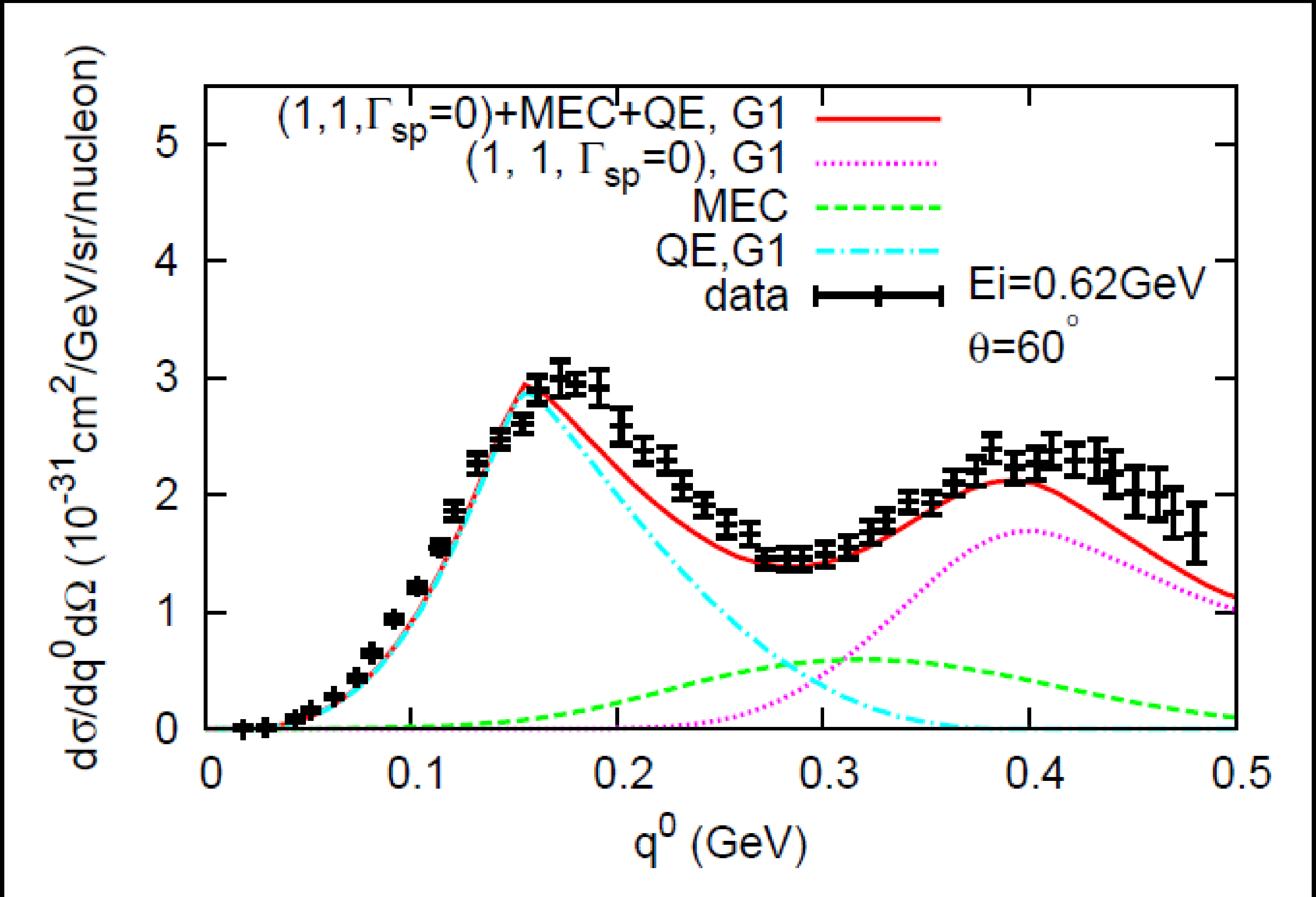
- Check: **incoherent** electro-production of pion from C12.

$$\Gamma_\Delta \rightarrow 120 \text{ MeV} + 40 \text{ MeV}$$



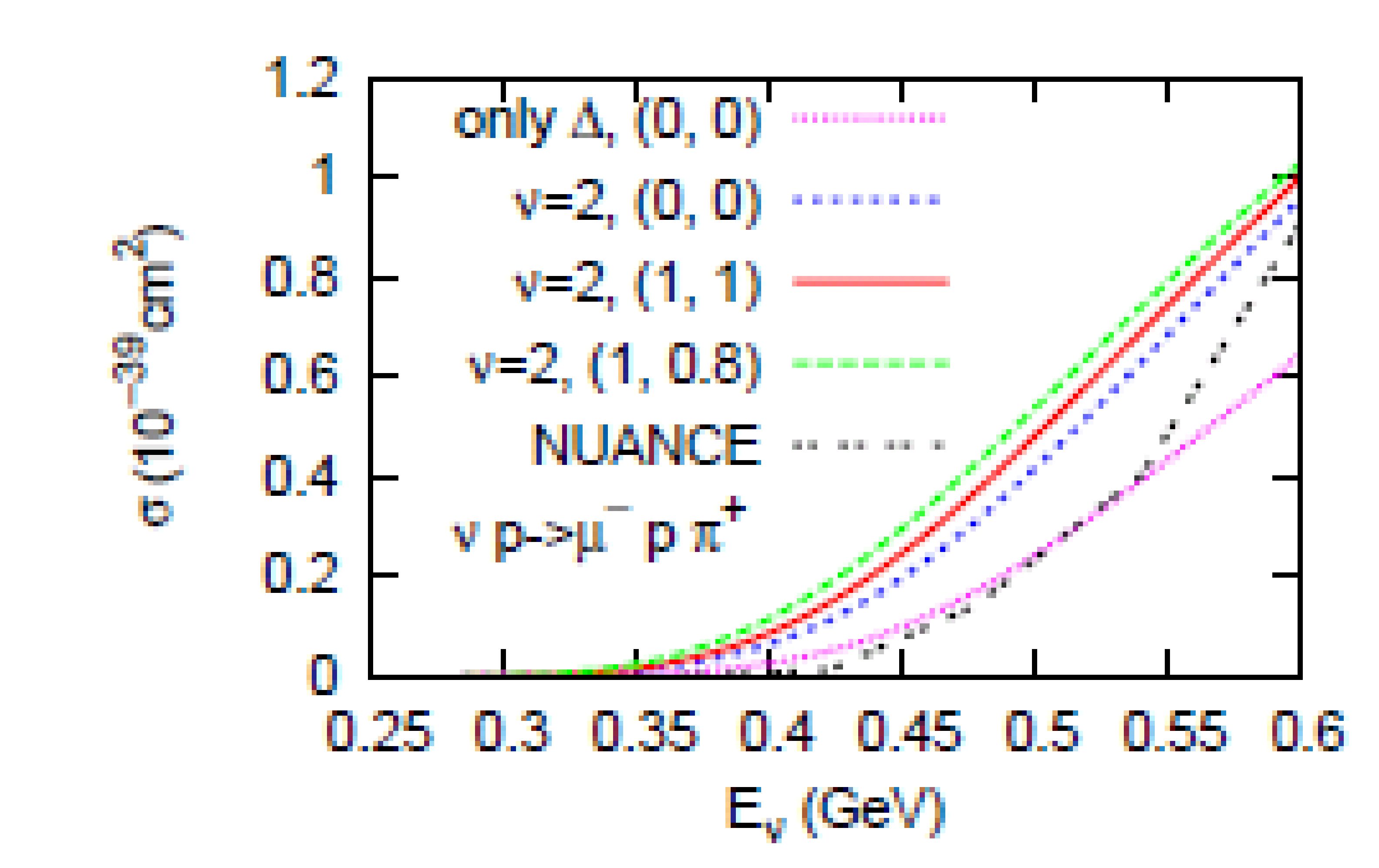
*E. Oset and L. Salcedo, NPA **468**, 631 (1987), P. Barreau et al., NPA **402**, 515 (1983).*

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

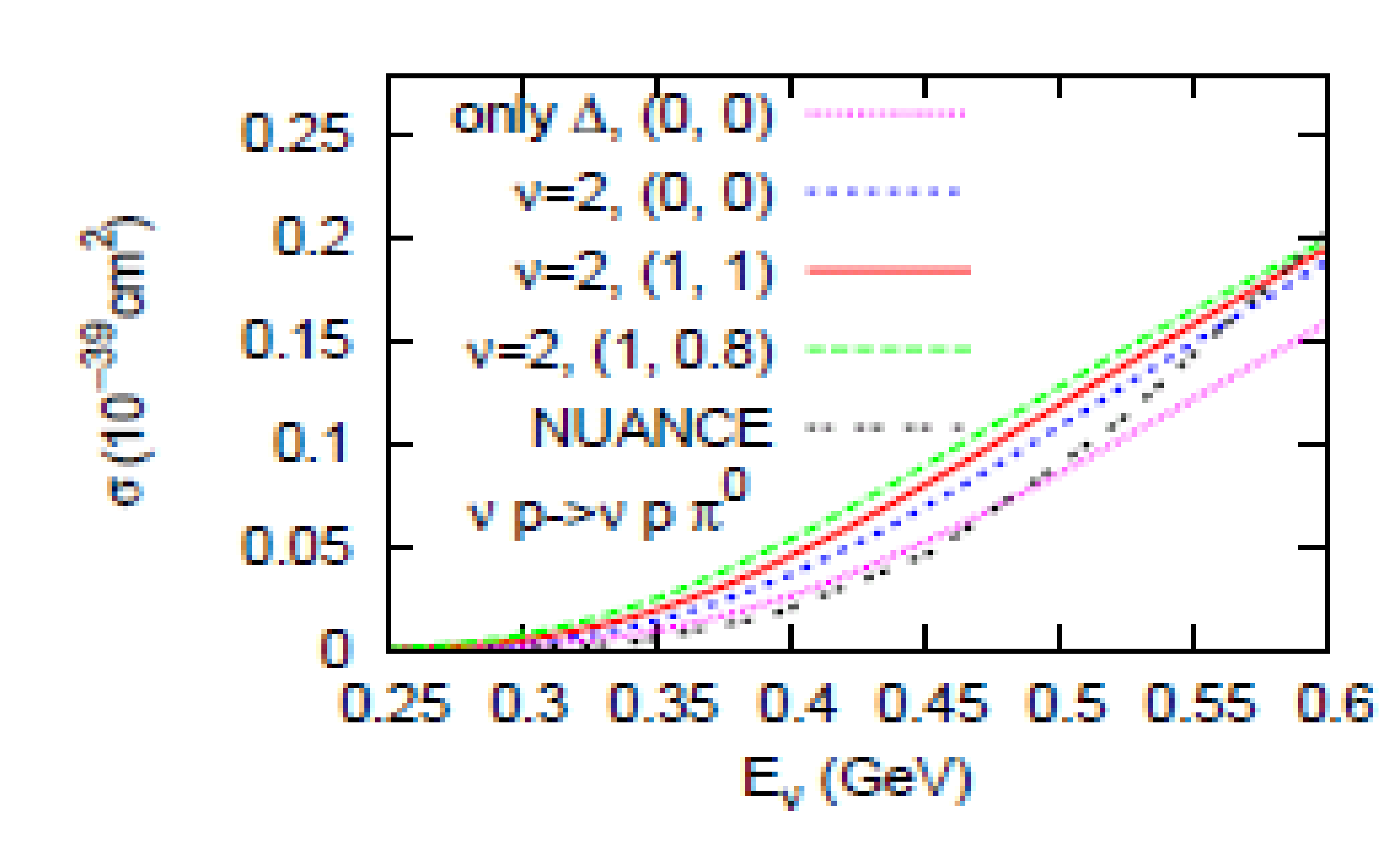


T. W. Donnelly (private communication).

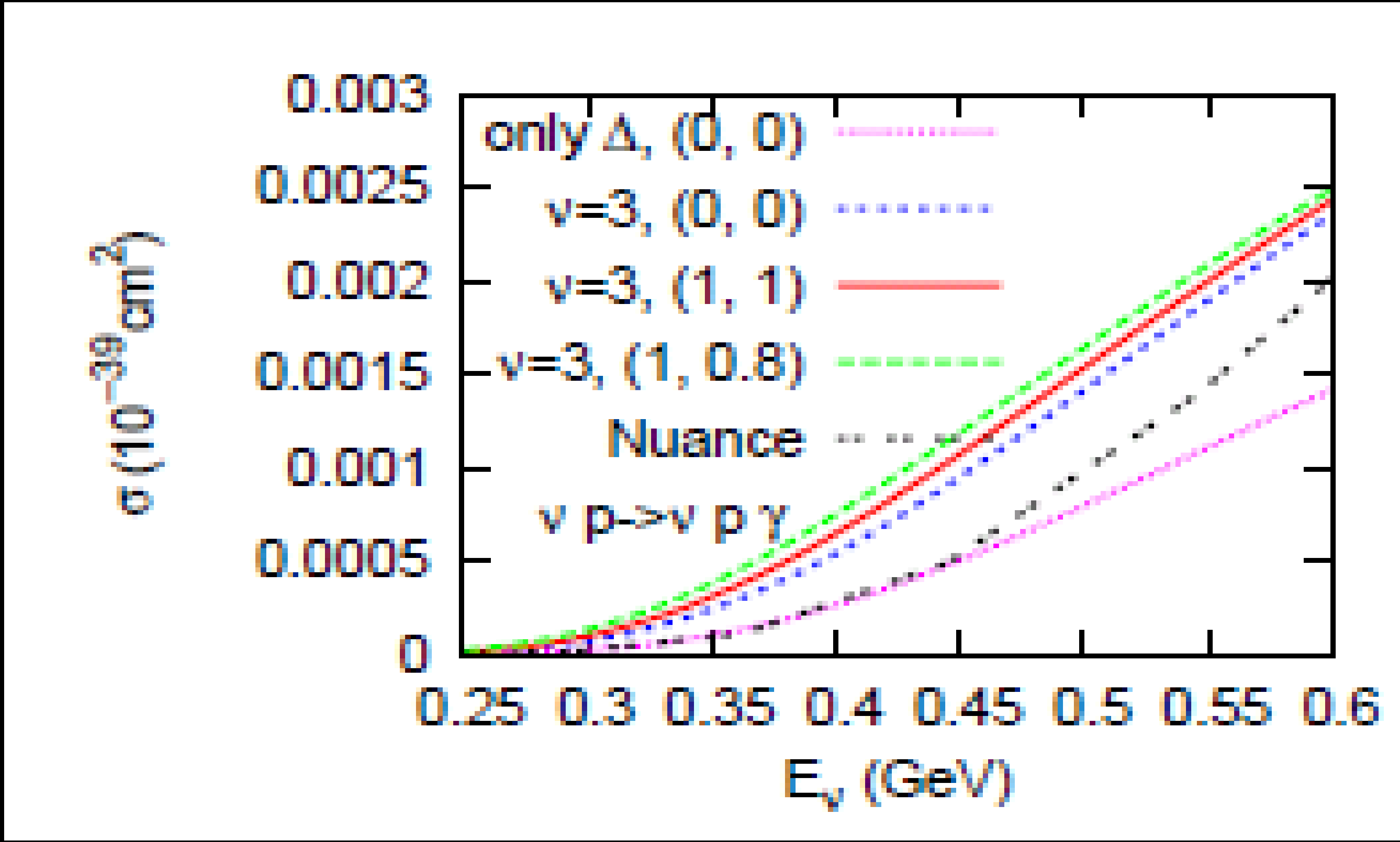
Incoherent neutrinoproduction of pion from C12



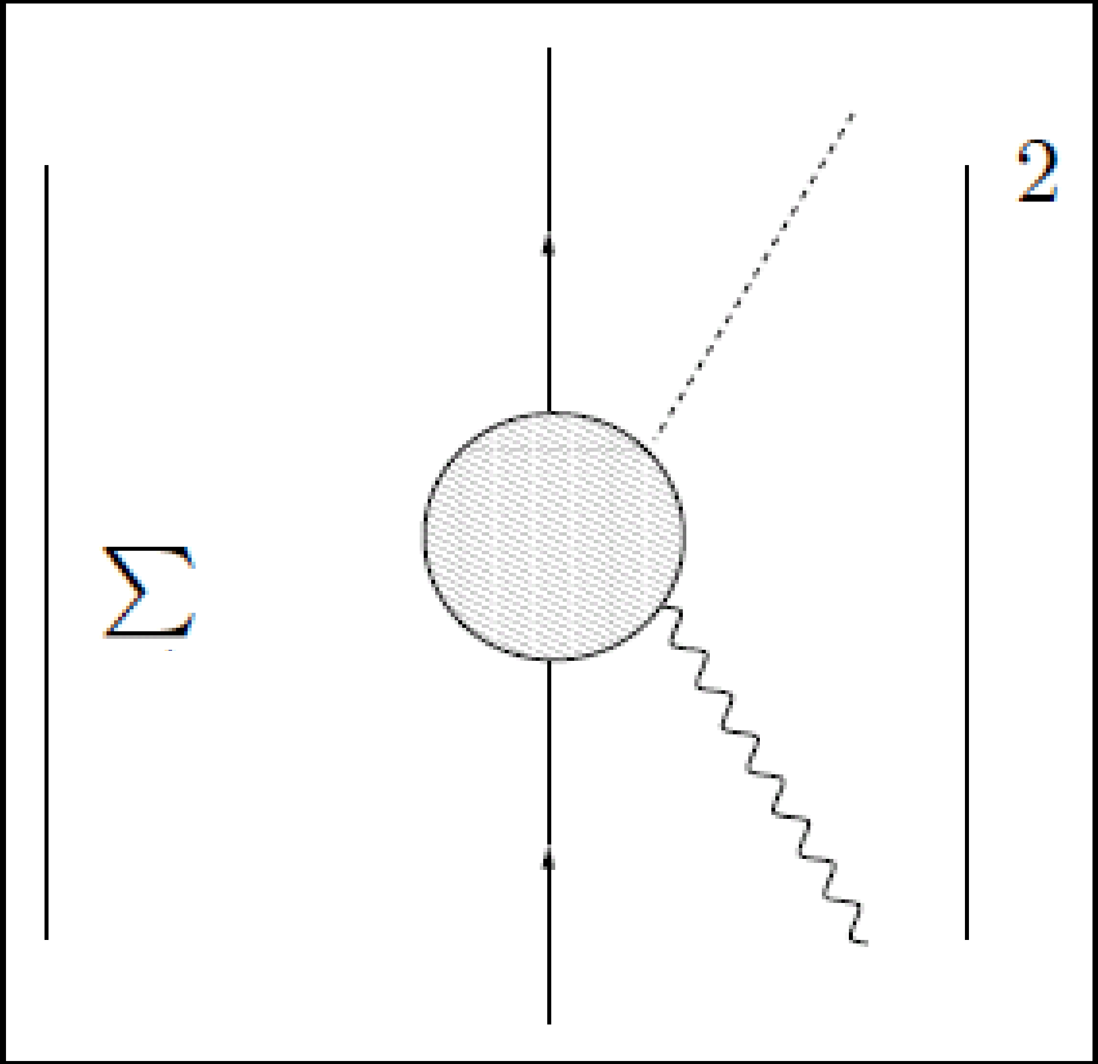
Incoh. neutrinoprod. of pion from C12



Incoh. neutrinoprod. of photon from C12



Coherent production of pion



Coherent production of pion

- "Optimal" approximation (factorization):

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

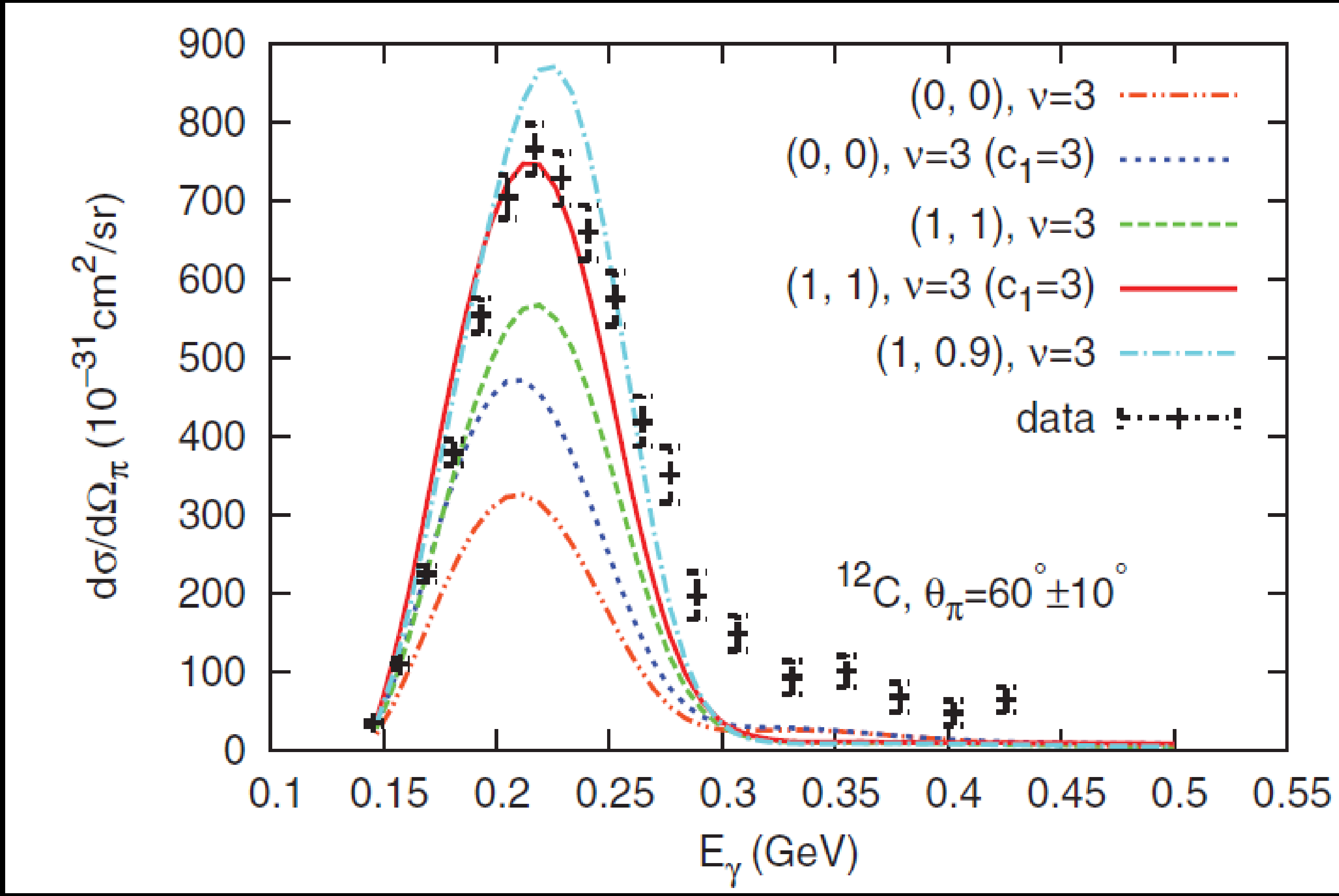
$$\approx \begin{cases} \int_A d\vec{r} e^{i(\vec{q}-\vec{k}_\pi)\cdot\vec{r}} \langle J^\mu_{had}(\vec{q}, \vec{k}_\pi, \vec{r})\rangle & \text{PW}, \\ \int_A d\vec{r} e^{i(\vec{q}-\vec{k}_\pi)\cdot\vec{r}} e^{-i\int_z^\infty \frac{\Pi(\rho,l)}{2|\vec{k}_\pi|}dl} \langle J^\mu_{had}(\vec{q}, \vec{k}_\pi,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

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

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

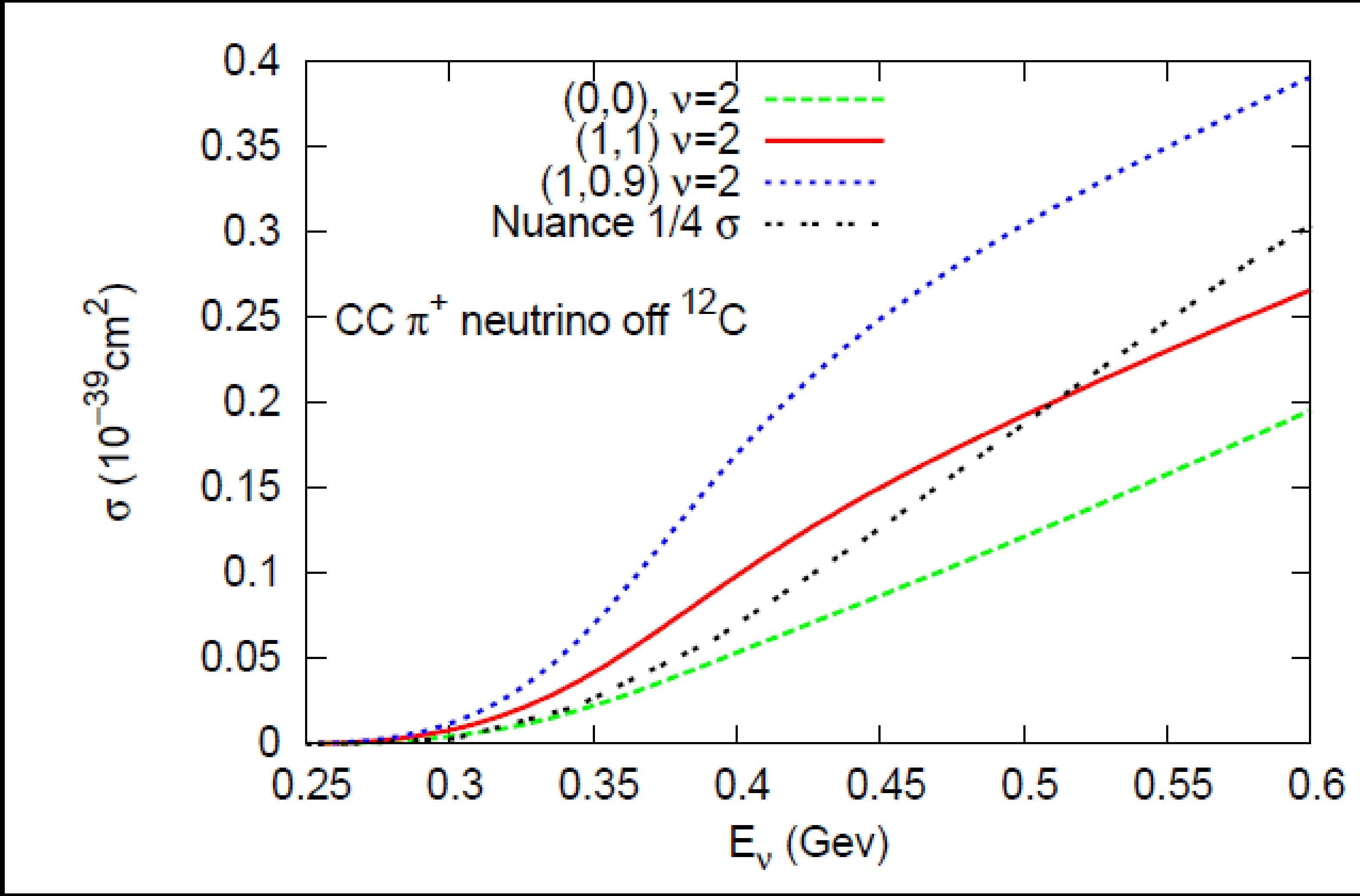
$$+ \rho_p(\vec{r})\frac{1}{2}\sum_{s_z}\frac{1}{p^{*0}_{ni}}\langle p, s_z, \frac{\vec{q}-\vec{k}_\pi}{2}|J^\mu_{had}(\vec{q}, \vec{k}_\pi)|p, s_z, \frac{\vec{k}_\pi-\vec{q}}{2}\rangle .$$

- Check: photo-production of pions from C12.



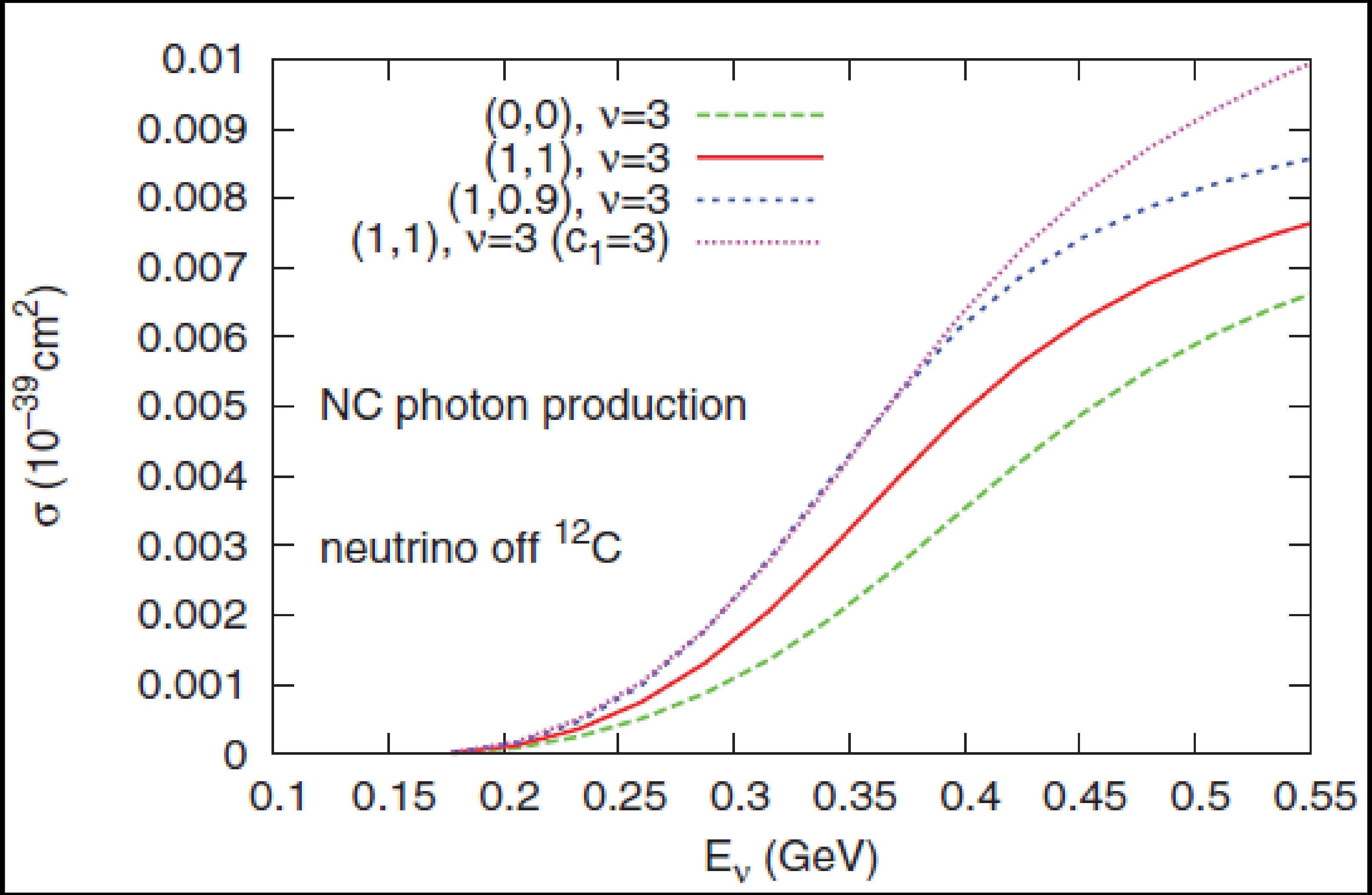
M. Schmitz, Ph.D. thesis, Johannes Gutenberg Universit¨at Mainz, 1996.
W. Peters, H. Lenske, and U. Mosel, NPA ***640****, 89 (1998).*

Coh. neutrinoprod. of pion from C12



Dr. Geralyn Zeller (private communication).

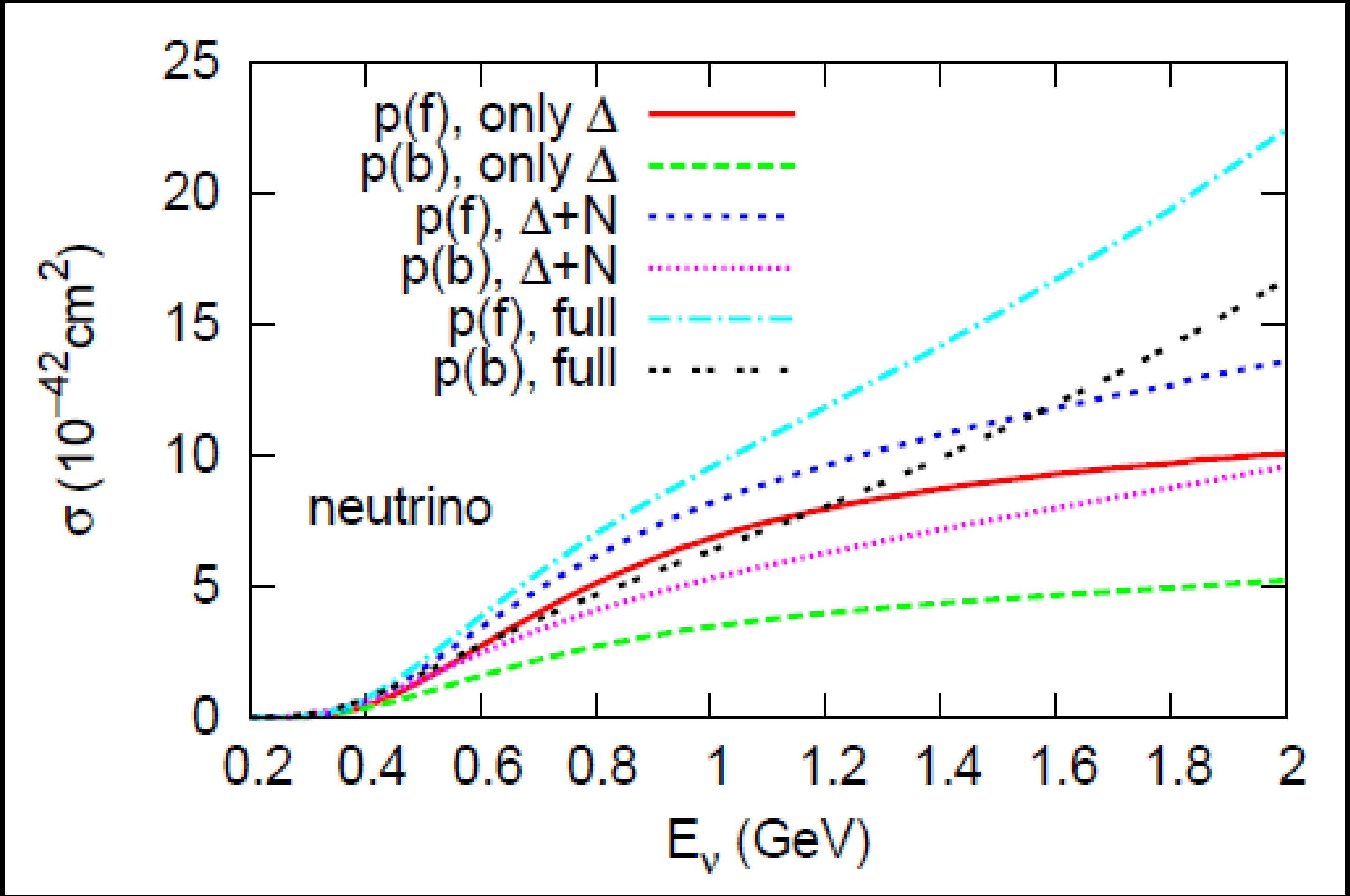
Coh. neutrinoprod. of photon from C12

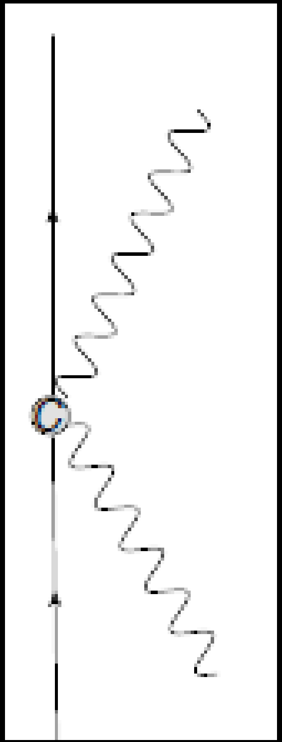


MiniBooNE NC photon

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

Extrapolation of previous results to higher energy

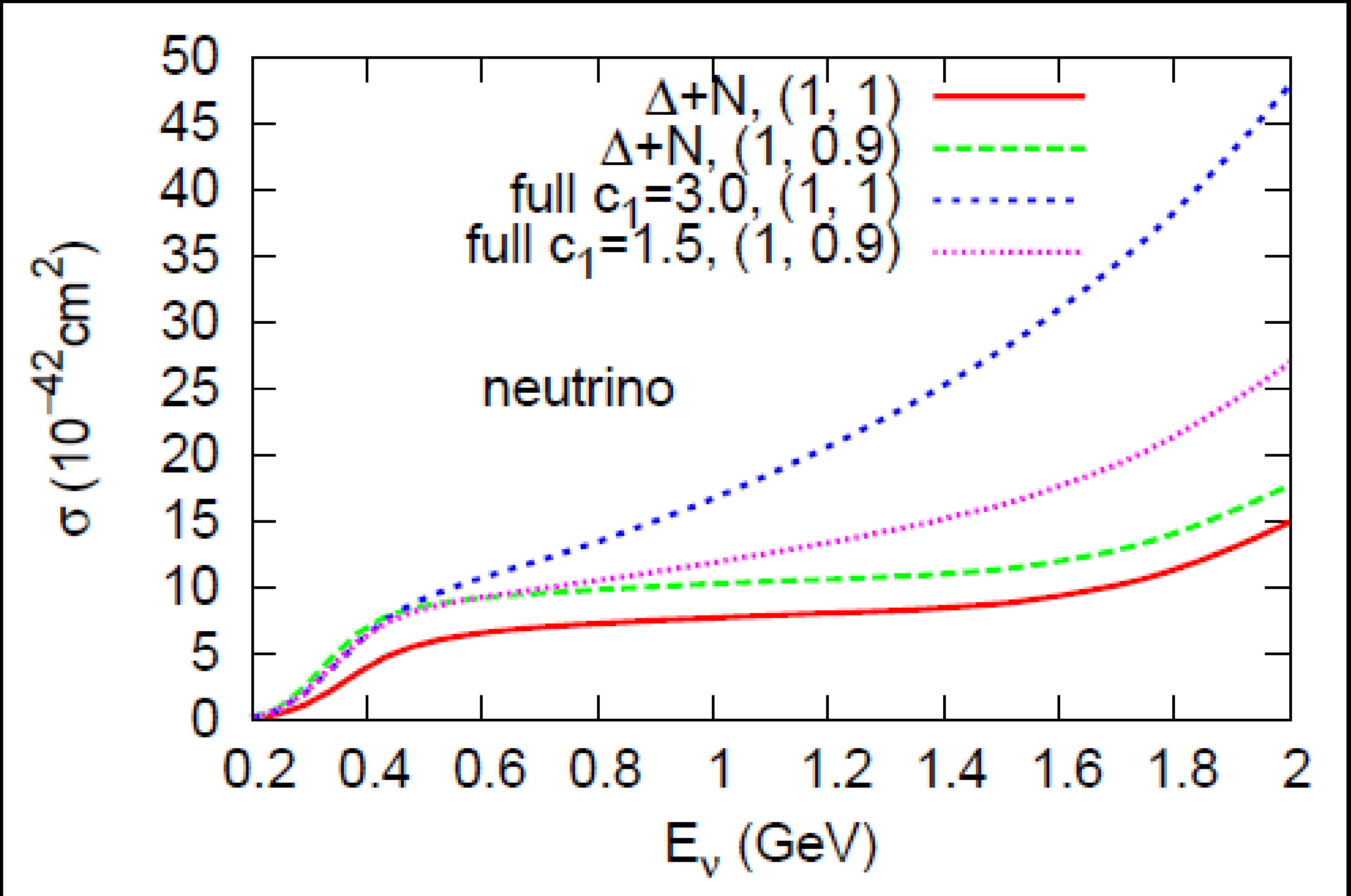




$$\frac{c_1}{M^2}\overline{N}\gamma^{\mu}N\,\mathrm{Tr}(\widetilde{a}^{\nu}\overline{F}^{(+)}_{\mu\nu})\,, \quad \frac{e_1}{M^2}\overline{N}\gamma^{\mu}\widetilde{a}^{\nu}N\overline{f}_{s\mu\nu}$$

MiniBooNE NC photon

Coherent production



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

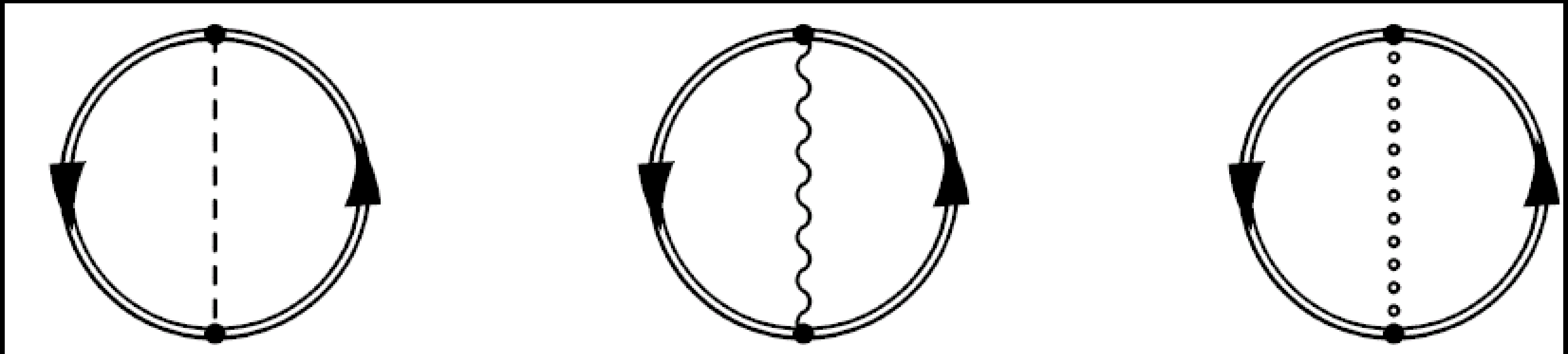
Summary

- QHD EFT→ a unified frame work for studying nuclear structure, EW response, nucleon, pion and Delta behavior in the medium
- Study EW pion and photon prod. in the QHD EFT, by using “LFG” (incoh.) and optimal factorization (coh.) approx.
- Extrapolate the EFT results to the 1—2 GeV lepton energy region; the kernel is from the EFT calculation.
- Calculate NC photons at MiniBooNE: the low energy excess can not be fully explained as NC photons.
- Interesting things to be done: a systematic study of Delta and pion dynamics in QHD EFT; go beyond “LFG”; treat the pion and photon prods., and quasi elastic scattering in this EFT.

Back up

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.

$$S_F = (S_F^{0(\frac{3}{2})} + S_F^{0(\frac{3}{2}\perp)}) + (S_F^{0(\frac{3}{2})} + S_F^{0(\frac{3}{2}\perp)})(\Sigma^{(\frac{3}{2})} + \Sigma^{(\frac{3}{2}\perp)})(S_F^{0(\frac{3}{2})} + S_F^{0(\frac{3}{2}\perp)}) + \cdots$$

$$= S_F^{0(\frac{3}{2})} + S_F^{0(\frac{3}{2})}\Sigma^{(\frac{3}{2})}S_F^{0(\frac{3}{2})} + \cdots$$

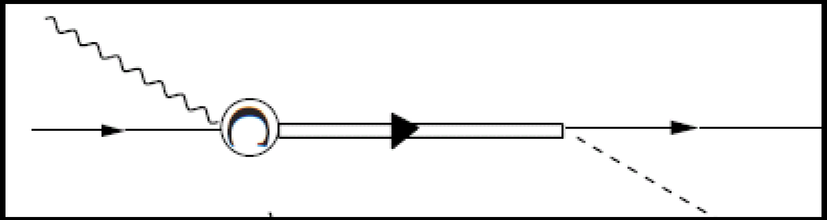
$$+ S_F^{0(\frac{3}{2}\perp)} + S_F^{0(\frac{3}{2}\perp)}\Sigma^{(\frac{3}{2}\perp)}S_F^{0(\frac{3}{2}\perp)} + \cdots$$

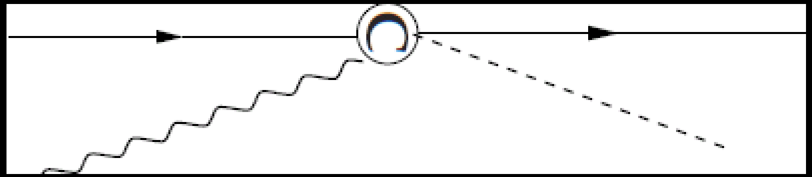
This can be generalized to other spins

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

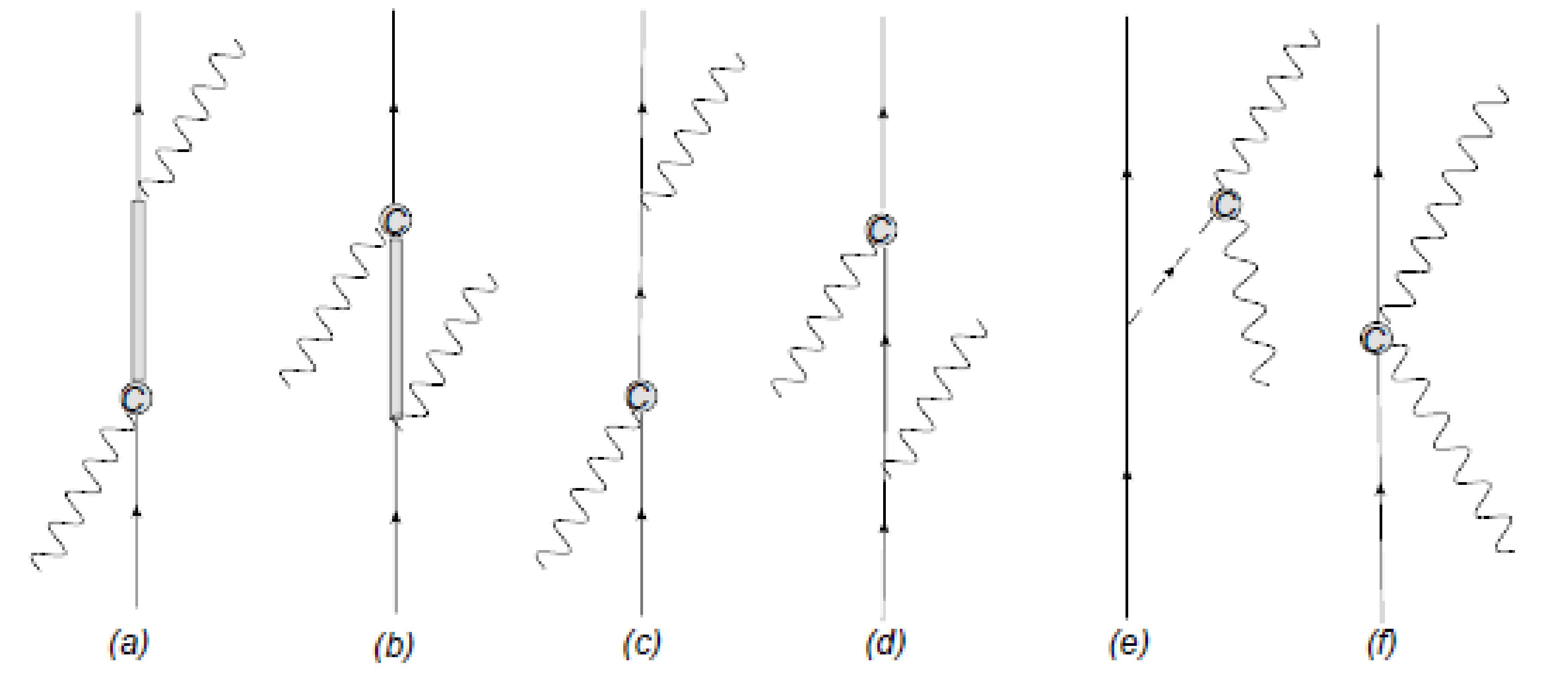
Spin-3/2 Particle in EFT

- 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 $\partial_\mu \overline{\psi}^\mu$





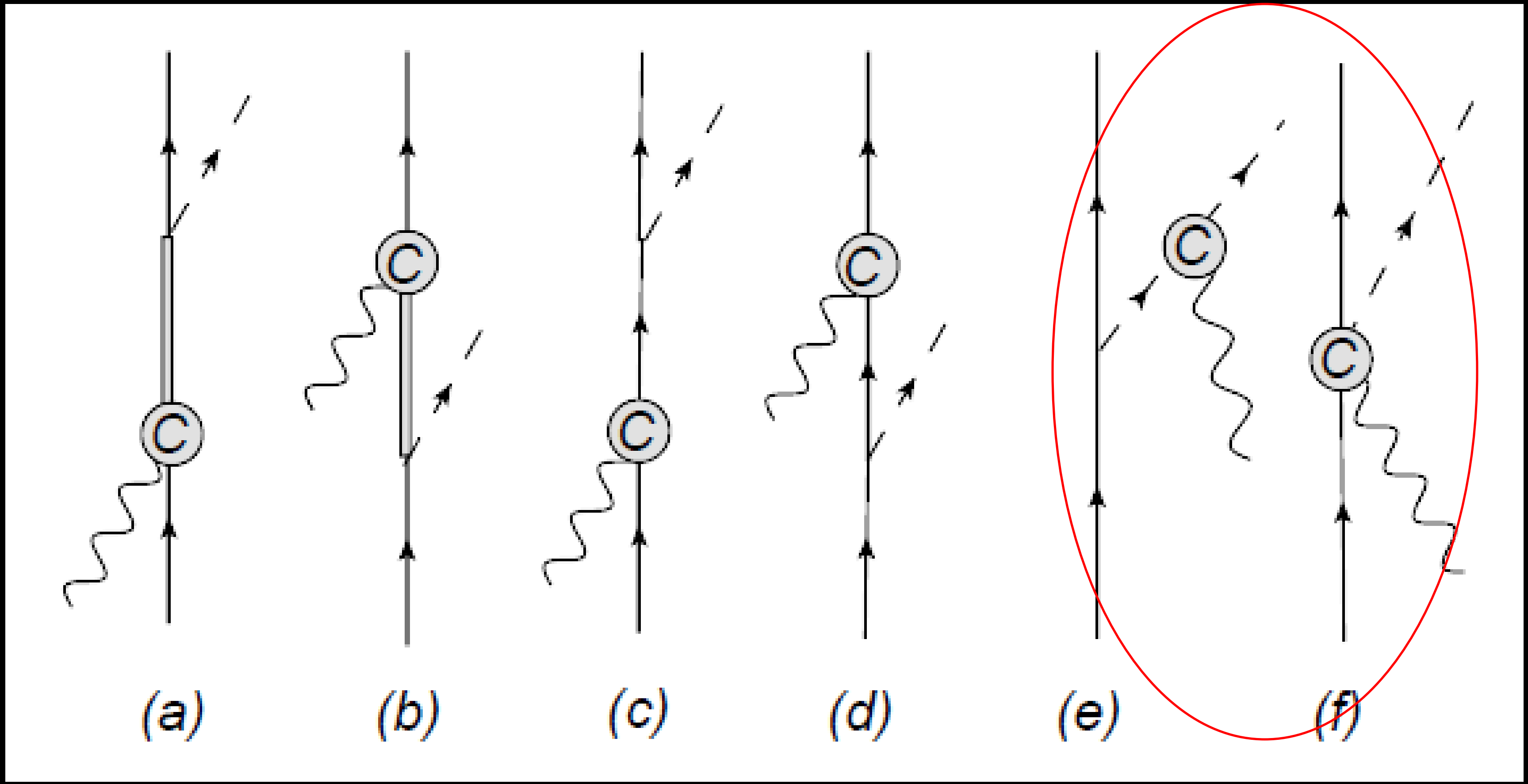
Kernel



- *(e) is small*
- *(f) are the anomalous terms with FFs included.*

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

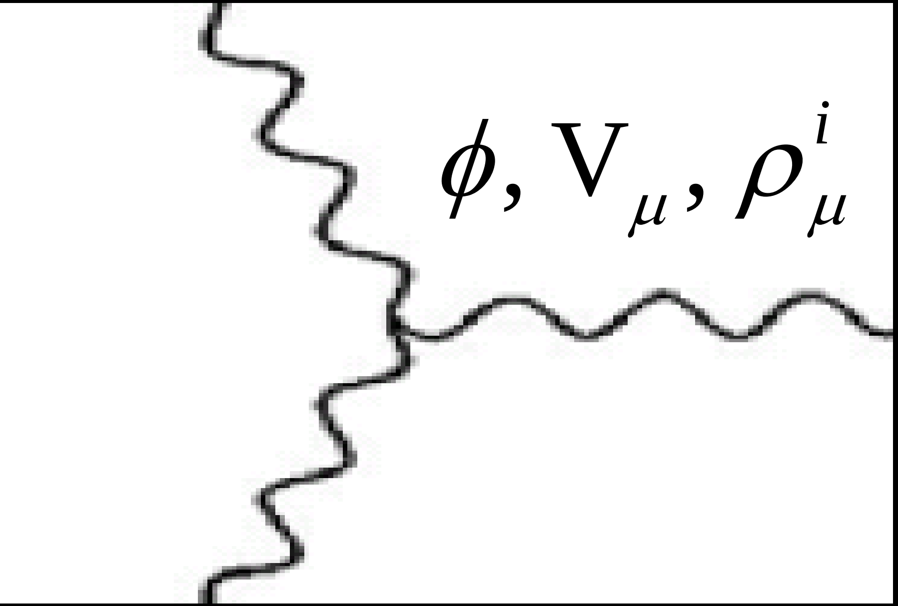
Benchmarks: pion prod.



- *FFs included in an EFT inspired way: CVC and PCAC.*
- *K-R, and anomalous diagrams included.*

Intro. to QHD

- NN interactions (relativistic field theory)
- Mesons nonlinear interactions



Three body force

A quick look:

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

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

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

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

B. Serot and X.Z., arXiv:1011.5913; Advances in QFT (InTech, 2012) (arXiv:1110.2760)

A quick look:

- Chiral symmetry in QCD:

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

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

- Its nonlinear realization at low energy EFT:

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

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

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

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

A quick look:

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

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

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

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

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

A quick look:

- …
- The lagrangian, baryon section:

$$\mathcal{L}_{N(\hat{\nu}\leqslant 3)} = \overline{N}\big(i\gamma^\mu[\widetilde{\partial}_\mu + ig_\rho\rho_\mu + ig_v V_\mu] + g_A\gamma^\mu\gamma^5\,\widetilde{a}_\mu - M + g_s\phi\big)N$$
$$- \frac{f_\rho g_\rho}{4M}\,\overline{N}\rho_{\mu\nu}\sigma^{\mu\nu}N - \frac{f_v g_v}{4M}\,\overline{N}V_{\mu\nu}\sigma^{\mu\nu}N - \frac{\kappa_\pi}{M}\,\overline{N}\,\widetilde{v}_{\mu\nu}\sigma^{\mu\nu}N + \frac{4\beta_\pi}{M}\,\overline{N}N\,\mathrm{Tr}(\widetilde{a}_\mu\widetilde{a}^\mu)$$

$$\mathcal{L}_\Delta = \frac{-i}{2}\,\overline{\Delta}^a_\mu\{\sigma^{\mu\nu}, (i\,\widetilde{\not\partial} - h_\rho\,\not\rho - h_v\,\not V - m + h_s\phi)\}_a^b\,\Delta_{b\nu} + \widetilde{h}_A\overline{\Delta}^a_\mu\;\widetilde{\not a}_a^b\gamma^5\Delta_b^\mu$$

$$\mathcal{L}_{\Delta,N,\pi} = h_A\overline{\Delta}^{a\mu}\,T_a^{\dagger\,iA}\,\widetilde{a}_{i\mu}N_A + \mathrm{c.c.},$$

A quick look:

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

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

Vector meson dominance (VMD)

A quick look:

- …
- Electroweak (EW) interactions:

$$\mathcal{L}_{\Delta,N,\mathrm{bg}} = \frac{ic_{1\Delta}}{M}\overline{\Delta}^a_\mu \gamma_\nu \gamma^5 T_a^{\dagger iA} F_i^{(+)\mu\nu} N_A + \frac{ic_{3\Delta}}{M^2}\overline{\Delta}^a_\mu i\gamma^5 T_a^{\dagger iA}(\widetilde{\partial}_\nu F^{(+)\mu\nu})_i N_A + \frac{c_{6\Delta}}{M^2}\overline{\Delta}^a_\lambda \sigma_{\mu\nu} T_a^{\dagger iA}(\widetilde{\partial}^\lambda \overline{F}^{(+)\mu\nu})_i N_A$$
$$- \frac{d_{2\Delta}}{M^2}\overline{\Delta}^a_\mu T_a^{\dagger iA}(\widetilde{\partial}_\nu F^{(-)\mu\nu})_i N_A - \frac{id_{4\Delta}}{M}\overline{\Delta}^a_\mu \gamma_\nu T_a^{\dagger iA} F_i^{(-)\mu\nu} N_A - \frac{id_{7\Delta}}{M^2}\overline{\Delta}^a_\lambda \sigma_{\mu\nu} T_a^{\dagger iA}(\widetilde{\partial}^\lambda F^{(-)\mu\nu})_i N_A + \mathrm{c.c.},$$

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

A quick look:

- Chiral symmetry in QCD:

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

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

B. Serot and X.Z., arXiv:1011.5913; Advances in QFT (InTech, 2012) (arXiv:1110.2760)

A quick look:

- Chiral symmetry in QCD
- The lagrangian, baryon section:

$$\mathcal{L}_{N(\hat{\nu}\leqslant 3)} = \overline{N}\big(i\gamma^\mu[\widetilde{\partial}_\mu + ig_\rho\rho_\mu + ig_v V_\mu] + g_A\gamma^\mu\gamma^5\widetilde{a}_\mu - M + g_s\phi\big)N$$
$$- \frac{f_\rho g_\rho}{4M}\overline{N}\rho_{\mu\nu}\sigma^{\mu\nu}N - \frac{f_v g_v}{4M}\overline{N}V_{\mu\nu}\sigma^{\mu\nu}N - \frac{\kappa_\pi}{M}\overline{N}\,\widetilde{v}_{\mu\nu}\sigma^{\mu\nu}N + \frac{4\beta_\pi}{M}\overline{N}N\,\mathrm{Tr}(\widetilde{a}_\mu\widetilde{a}^\mu)$$

$$\mathcal{L}_\Delta = \frac{-i}{2}\overline{\Delta}^a_\mu\{\sigma^{\mu\nu}, (i\,\widetilde{\not{\partial}} - h_\rho\,\not{\rho} - h_v\,\not{V} - m + h_s\phi)\}^b_a\,\Delta_{b\nu} + \widetilde{h}_A\overline{\Delta}^a_\mu\;\widetilde{\not{a}}^b_a\gamma^5\Delta^\mu_b$$

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

A quick look:

- Chiral symmetry in QCD
- The lagrangian, baryon section.
- **The lagrangian, meson section:**

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

Vector meson dominance (VMD)

A quick look:

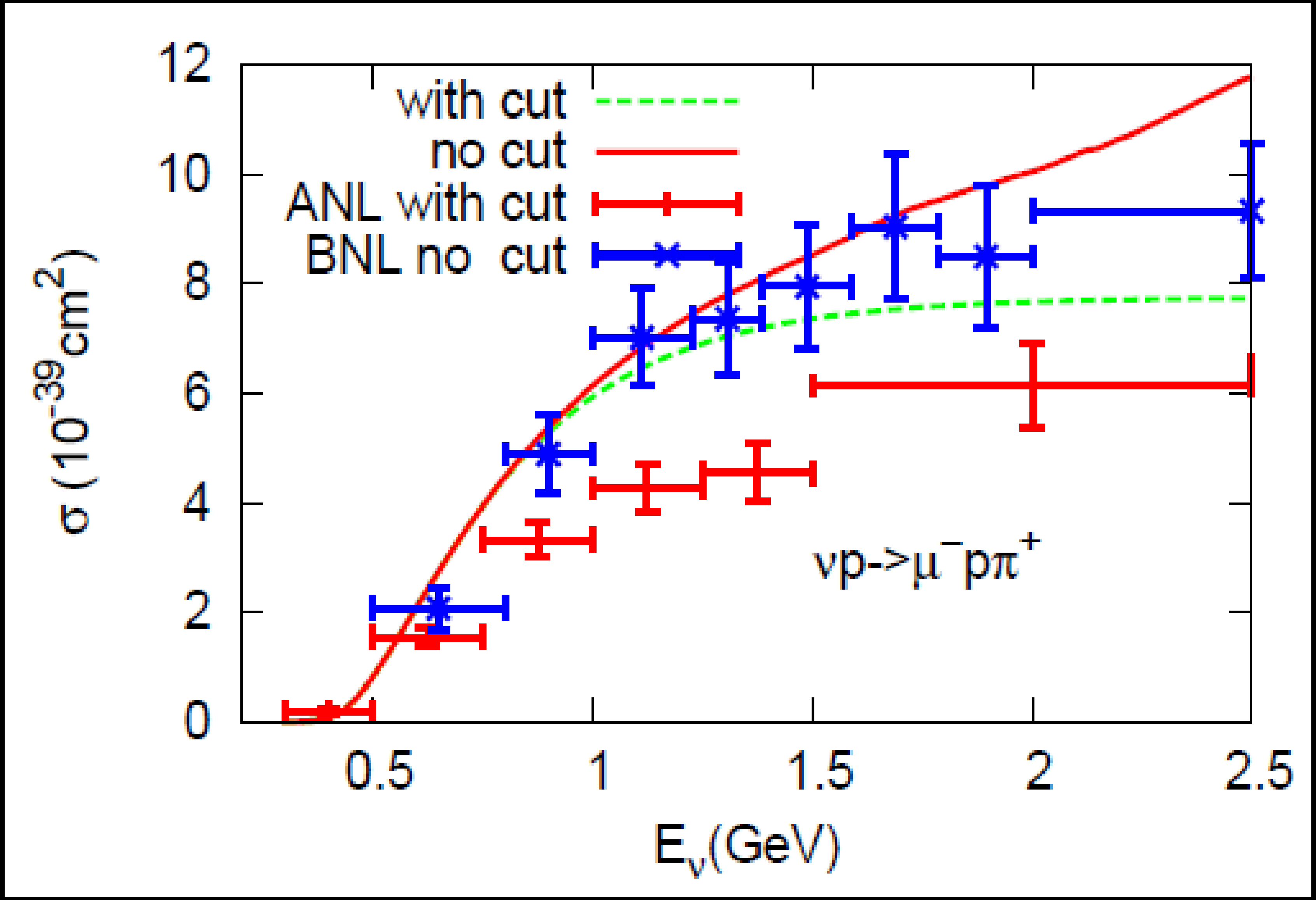
- …
- Electroweak (EW) interactions:

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

A quick look (recap)

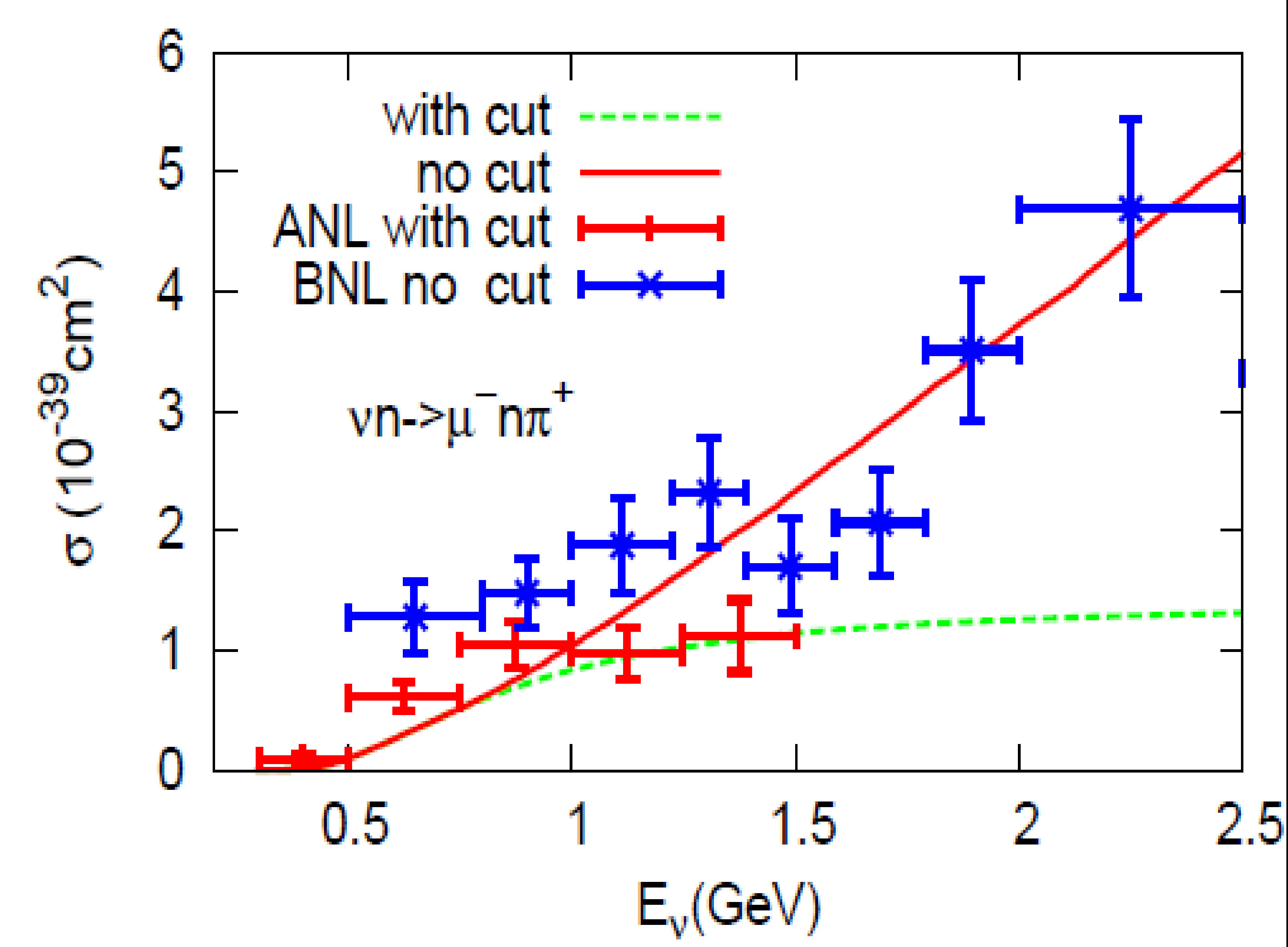
- Chiral symmetry
- The lagrangian
- Electroweak (EW) interactions (CVC and PCAC)

Benchmarks



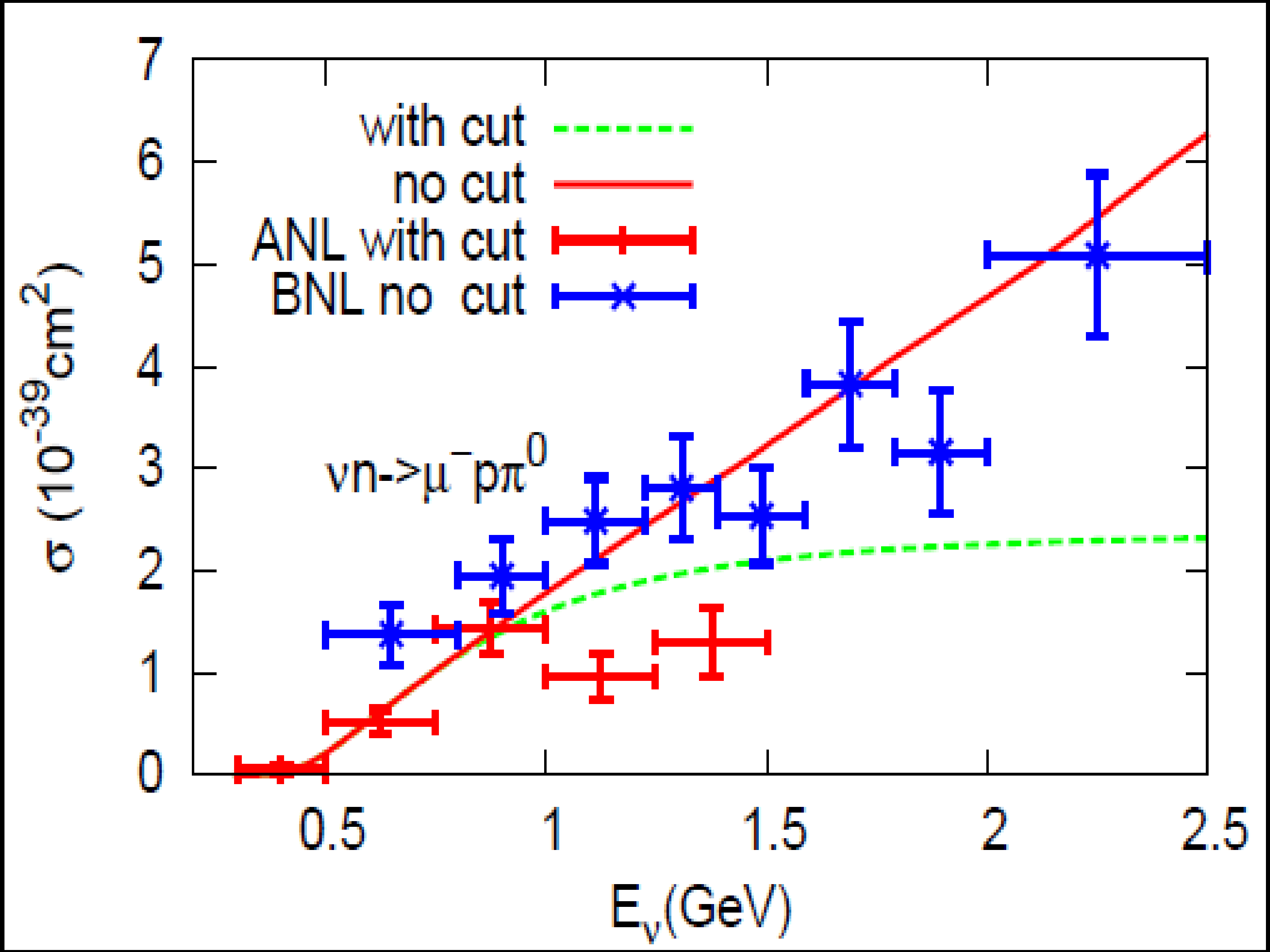
with cut
no cut
ANL with cut
BNL no cut
νp->μ⁻pπ⁺
σ (10⁻³⁹cm²)
Eν(GeV)
0
2
4
6
8
10
12
0.5
1
1.5
2
2.5

Benchmarks



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

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