Implication of Chiral Symmetry on Neutral Weak Pion Production off a Nucleon

De-Liang Yao
姚德良

Hunan University

XVIII International Conference on Hadron Spectroscopy and Structure
16-21 August, 2019, Guilin, China

In collaboration with L. Alvarez-Ruso, A. H. Hiller-Blin and M. J. Vicente-Vacas

Phys. Rev. D98 (2018) 076004, Phys. Lett. B794(2019)109-113

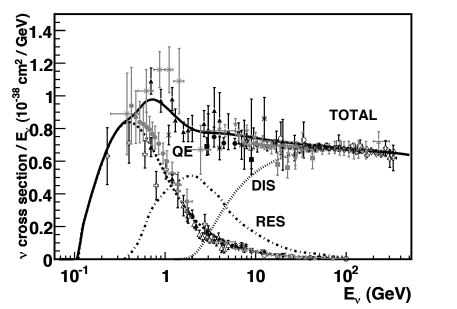
Contents

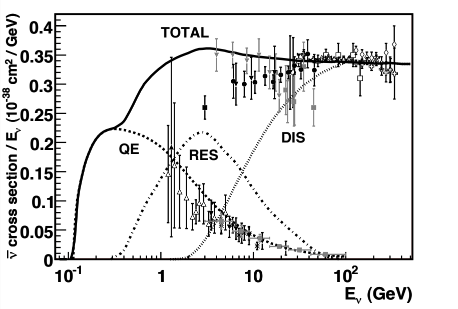
Why single pion production?

- Two types of processes:
  Charged-Current (CC) & Neutral-Current (NC) induced.
- Important contribution to the inclusive neutrino-nuclei (νA) cross section

[Formaggio, Zeller, Rev. Mod. Phys. (2012)]

  - **RES**: Predominantly $\Delta(1232)$ excitation $\Longrightarrow \Delta \to \pi N$ (99.4%)
  - Prediction by NUANCE generator

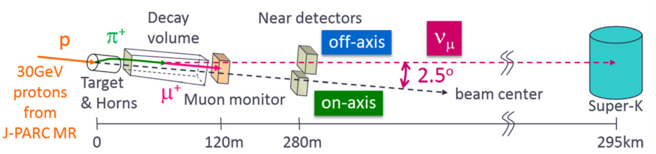




Total cross section per nucleon. Left: ν-CC; Right: $\bar{\nu}$-CC.

Why single pion production?

- Oscillation experiments (e.g. T2K)
  - survival probability of ν_μ: $P(\nu_\mu) = 1 - \sin^2 2\theta_{\mu\tau} \cdot \sin^2 \frac{\Delta m_{23} L}{E_\nu}$



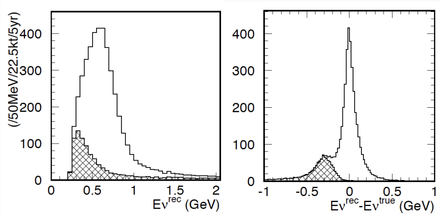
- Source of experimental uncertainties

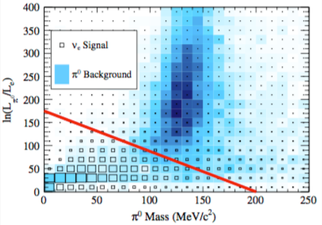
CC 1π:

- ☞ CCQE-like events: misiden. of pion
- ☞ to be subtracted for a good E_ν

NC 1π:

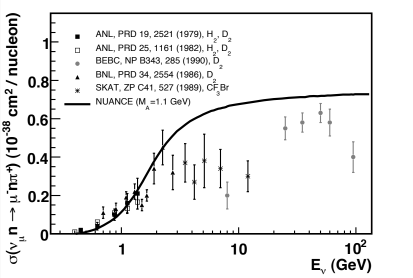
- ☞ e-like background to $\nu_\mu \to \nu_e$ searches
- ☞ improved at T2K with a π^0 rejection cut

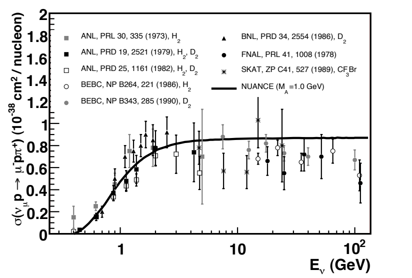


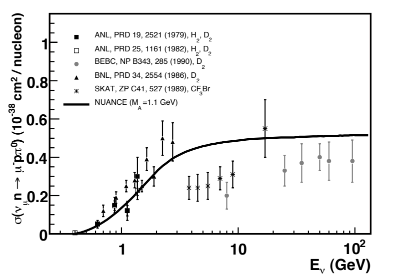


Experimental data

- CC1π





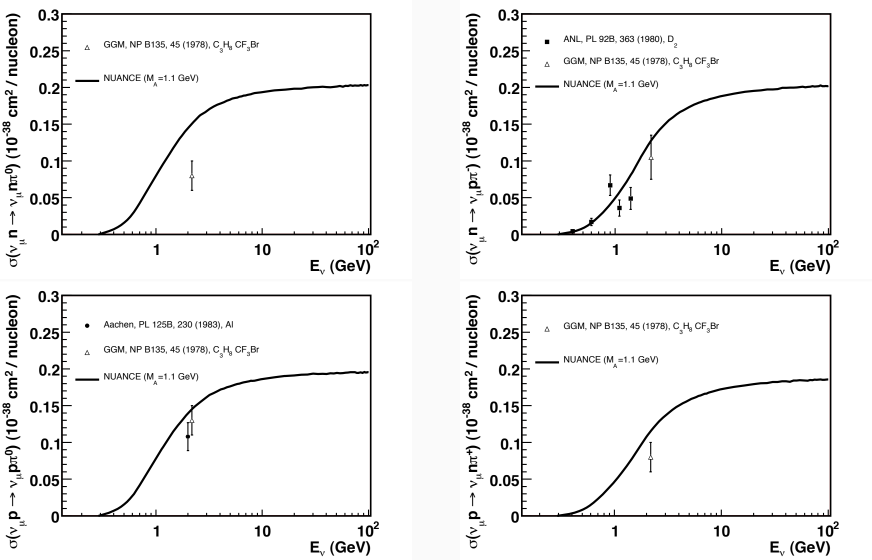


[Formaggio, Zeller, Rev. Mod. Phys. (2012)]

Experimental data

- NC1π: Very rare data below 1 GeV

[Formaggio, Zeller, Rev. Mod. Phys. (2012)]



Status of theoretical studies

- Isobar Models
  - Δ and heavier resonances $\rightarrow$ nucleon-to-resonance form factors:
    [e.g., Llewellyn Smith, Phys. Rep. 3 (1972)] [Fogli and Nardulli, Nucl. Phys. B160 (1979)] [Rein and Sehgal, Ann. Phys. (1981)]
    - Real form factor from quark models
    - Conserved vector current $\rightarrow$ related to electromagnetic ones extracted from electron scattering data
    - PCAC $\rightarrow$ off-diagonal Goldberger-Treiman (GT) relation for the axial couplings
  - Nonresonant mechanisms
    [Fogli and Nardulli, Nucl. Phys. B160 (1979)] [Bijtebier, Nucl. Phys. B21 (1970)] [Alevizos et al., J. Phys. G 3(1977)]

- Hernandez-Nieves-Valverde (HNV) Model
  - Δ resonances & non-resonant terms $\rightarrow$ constrained by chiral symmetry at threshold [Hernandez, Nieves and Valverde, Phys. Rev. D (2007)]
  - Final state interaction: imposing Watson's theorem [Alvarez-Ruso et al., Phys. Rev. D 93 (2016)]
  - Unphysicsal spin-1/2 components: adding new contact terms
    [Hernandez and Nieves, Phys. Rev. D (2017)]

Status of theoretical studies

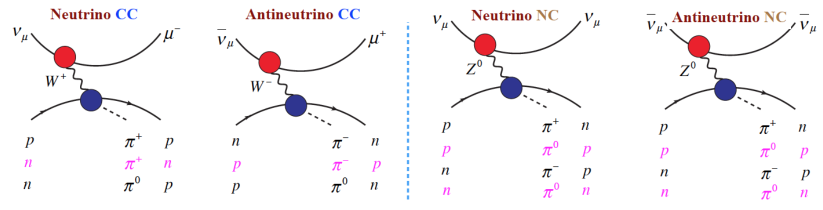
- Other Models:
  - Dynamical model: coupled-channel Lippmann Schwinger equation
    - Fulfilling Watson's theorem
    - PCAC $\rightarrow$ partially constrain the axial current in terms of πN scattering amplitude fitted to data [Nakamura, Kamano and Sato, Phys. Rev. D (2015)]
  - Chiral effective model with π, N, Δ together with σ, ρ, ω
    - Power counting only for tree diagrams [Serot and Zhang, Phys. Rev. C (2012)]
  - etc.

- Low energy regime:
  Chiral symmetry + Power counting + Perturbative Unitarity

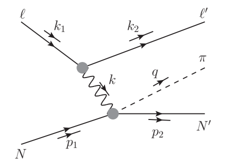
- Baryon Chiral Perturbation Theory (BChPT)
  - Low-Energy theorems (axial only) at threshold using heavy baryon formalism [Bernard, Kaiser and Meißner, Phys. Lett. B (1994)]
  - Our work: One-loop analyses in relativistic BChPT with explicit Δs [DLY, Alvarez-Ruso, Hiller-Blin and Vicent-Vacas, Phys. Rev. D (2018)] [DLY, Alvarez-Ruso and Vicent-Vacas, Phys. Lett. B (2019)]

Leptonic and Hadronic parts

- Physical channels (3 for CC & 4 for NC)



- Amplitude structure:
  - One-boson approximation and $k^2 \ll M_B^2$
  - Leptonic part L_ν is well-known; Hadronic part H_μ needs to be investigated.



$$= i(2\pi)^4\delta^{(4)}(k_1+p_1-k_2-p_2-q)\frac{iN^2}{M_B^2}\underbrace{\langle \ell'|J_\nu(0)|\ell\rangle}_{L^\mu}\underbrace{\langle \pi N'|J_\mu(0)|N\rangle}_{H_\mu}$$

Convenient isospin decomposition

- Isospin even (+), isospin odd (-), isoscalar (0)

$$\langle \pi^b N' | J_\mu^a(0) | N \rangle = \chi_f^\dagger \left[\delta^{ba} H_\mu^+ + i\epsilon^{bac}\tau^c H^- + \tau^b H_\mu^0 \right] \chi_i$$

- The physical amplitudes constructed from the isospin amplitudes

$$H_\mu(\text{physical process}) \quad = \quad a_+ H_\mu^+ + a_- H_\mu^- + a_0 H_\mu^0$$

	Physical Process	a_+	a_-	a_0
NC	$Z^0 p \to p\pi^0$	1	0	1
	$Z^0 n \to n\pi^0$	1	0	-1
	$Z^0 n \to p\pi^-$	0	$-\sqrt{2}$	$\sqrt{2}$
	$Z^0 p \to n\pi^+$	0	$\sqrt{2}$	$\sqrt{2}$
CC	$W^+ p \to p\pi^+ \ / \ W^- n \to n\pi^-$	1	-1	0
	$W^+ n \to n\pi^+ \ / \ W^- p \to p\pi^-$	1	1	0
	$W^+ n \to p\pi^0 \ / \ W^- p \to n\pi^0$	0	$\sqrt{2}$	0

- The CC and NC amplitudes are related to each other
  - ☞ For CC, $H_\mu^\pm = \sqrt{2}\cos\theta_C (V_\mu^\pm - A_\mu^\pm)$, $\quad H_\mu^0 = 0.$
  - ☞ For NC, $H_\mu^\pm = (1 - 2\sin^2\theta_W) V_\mu^\pm - A_\mu^\pm$, $\quad H_\mu^0 = (-2\sin^2\theta_W) V_\mu^0$

The Lagrangian

- Covariant baryon chiral perturbation theory in SU(2) case.
- Nucleonic Lagrangian [Fettes et al Ann. Phys. (2000)]

$$\mathcal{L}_N = \bar{N}\big[i\not{D} - m + \frac{g}{2}\not{u}\gamma_5\big]N + \bar{N}\big[c_j\mathcal{O}_j^{(2)} + d_k\mathcal{O}_k^{(3)}\big]N + \cdots$$

- Purely mesonic Lagrangian [Gasser and Leutwyler, Ann. Phys. (1984)] [Gasser et al., Nucl. Phys. B307 (1988)]

$$\mathcal{L}_\pi = \frac{F^2}{4}\mathrm{Tr}[\Delta_\mu U(\Delta^\mu U)^\dagger + \chi U^\dagger + U\chi^\dagger] + \sum_{j=3,4,6}\ell_j\mathcal{O}_j^{(4)}$$

- Electro-weak interactions enter through external fields [c.f. Scherer and Schindler, 2011, Springer]
  - ☞ Charged weak bosons $W^\pm$:

$$r_\mu = 0, \quad l_\mu = -\frac{g}{\sqrt{2}}(V_{ud}W_\mu^+\tau_+ + h.c.)$$

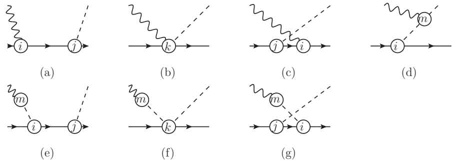
  - ☞ Neural weak boson Z^0:

$$r_\mu = e\tan(\theta_W)Z_\mu^0\frac{\tau_3}{2}, \quad l_\mu = -\frac{g}{\cos(\theta_W)}Z_\mu^0\frac{\tau^3}{2} + e\tan(\theta_W)Z_\mu\frac{\tau_3}{2},$$

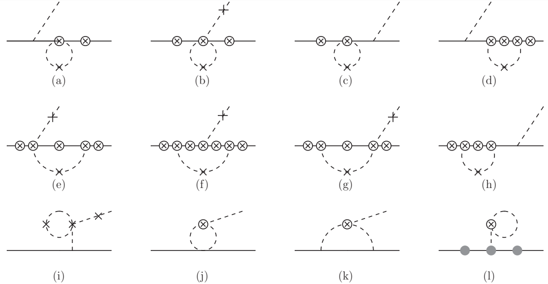
$$v_\mu^{(s)} = \frac{e\tan(\theta_W)}{2}Z_\mu^0$$

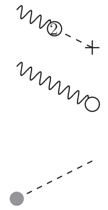
The hadronic amplitude

- Tree diagrams up through $O(p^3)$:



- All possible loop diagrams at $O(p^3)$:





89 diagrams & wave function renormalization & EOMS

Necessity of the Δ resonance

- Δ is strongly coupled to the final πN system
  - BR($\Delta \to \pi N$) $\simeq 99.4\%$
  - Close to πN threshold: $\Delta = m_\Delta - m_N \sim 300$ MeV
- Strategy: the δ-counting [Pascalutsa and Phillips, Phys. Rev. C67 (2012)]
  - hierachy of scales: $M_\pi \sim p \ll \Delta \ll \Lambda \sim 4\pi F_\pi$
  - expanding parameter: $\delta = \frac{\Delta}{\Lambda} \sim \frac{M_\pi}{\Delta} \sim \frac{p}{\Delta} \longrightarrow \frac{1}{\not{p} - m_\Delta} = \frac{1}{\not{p} - m_N - \Delta} \sim p^{-\frac{1}{2}}$
- Counting rule:

$$\text{chiral order } D = 4L + \sum_k kV^{(k)} - 2I_\pi - I_N - \frac{1}{2} I_\Delta$$

  - only trees of $O(p^{3/2})$ and $O(p^{5/2})$
  - No loop diagrams with explicit Δ up through $O(p^3)$
- The width effect

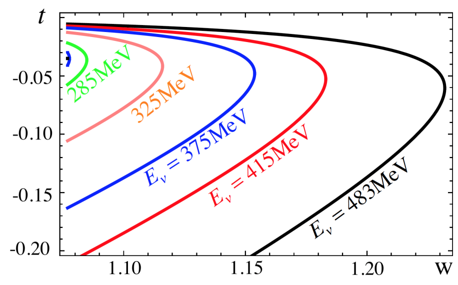
$$\frac{1}{m_\Delta^2 - s_\Delta} \to \frac{1}{m_\Delta^2 - i m_\Delta \Gamma_\Delta(s_\Delta) - s_\Delta}$$

Energy dependent width $\Gamma_\Delta(s_\Delta)$ calculated in the same scheme

[Gegelia et al, Phys. Lett. B(2016)]

Numerical settings

- Energies considered for $E_\nu \in [E_{\nu,th}, E_{\nu,\max} \equiv E_{\nu,th} + M_\pi]$
  - E.g., $E_{\nu,\max} = 415$ MeV for CC; $E_{\nu,\max} = 289$ MeV for NC
  - Well below the Δ peak $\rightarrow$ δ-counting is valid



W: CM energy of the final πN system (CC for example)

- Data for neutrino-induced single pion production off nucleons are very rare
- Values of the leading order constants

F_π	M_π	m_N	m_Δ	g_A	h_A
92.21	138.04	938.9	1232 MeV	1.27	1.43 ± 0.02

Low energy constants beyond LO

- Most of the LECs (16 out of 23) are previously determined from other processes or observables

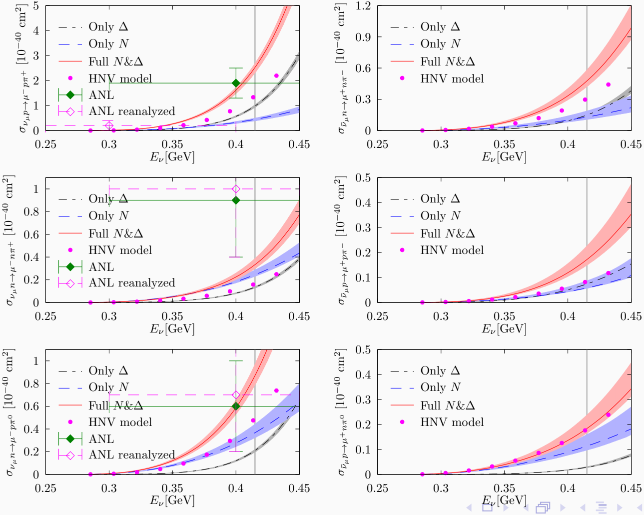
	LEC	Value	Source
$\mathcal{L}_{\pi\pi}^{(4)}$	$\bar{\ell}_6$	16.5 ± 1.1	$\langle r^2 \rangle_\pi$ [Gasser, Leutwyler 1984]
$\mathcal{L}_{\pi N}^{(2)}$	$\tilde{c}_1$	-1.00 ± 0.04	πN scattering [Alarcon et al. 2013 & Chen et al. 2013]
	$\tilde{c}_2$	1.01 ± 0.04	
	$\tilde{c}_3$	-3.04 ± 0.02	
	$\tilde{c}_4$	2.02 ± 0.01	
	$\tilde{c}_6$	1.35 ± 0.04	μ_p and μ_n [Bauer et al. 2012 & PDG2016]
	$\tilde{c}_7$	-2.68 ± 0.08	
$\mathcal{L}_{\pi N}^{(3)}$	d_{1+2}^r	0.15 ± 0.20	πN scattering [Alarcon et al. 2013 & Chen et al. 2013]
	d_3^r	-0.23 ± 0.27	
	d_5^r	0.47 ± 0.07	
	d_{14-15}^r	-0.50 ± 0.50	
	d_{18}^r	-0.20 ± 0.80	
	d_6^r	-0.70	$\langle r_E^2 \rangle_N$ [Fuchs et al. 2014]
	d_7^r	-0.47	
	d_{22}^r	0.96 ± 0.03	$\langle r_A^2 \rangle_N$ [Yao et al. 2017]
$\mathcal{L}_{\pi N\Delta}^{(2)}$	b_1	$(4.98 \pm 0.27)/m_N$	$\Gamma_\Delta^{\rm em}$ [Bernard et al 2012]

- The remaining unknown LECs → set to natural size

$$d_j^r = 0.0 \pm 1.0\ \mathrm{GeV}^{-2}\ , \quad j \in \{1, 8, 9, 14, 20, 21, 23\}$$

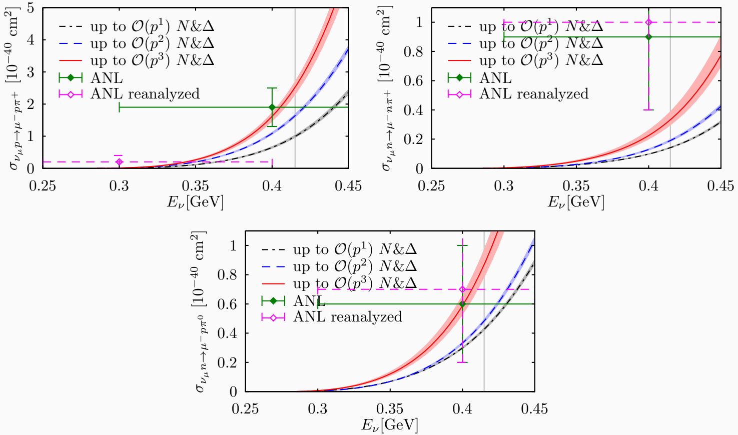
Cross sections for CC1π

- Fairly good agreement with the ANL data for most of the channels except for $\nu_\mu n \to \mu^- n \pi^+$



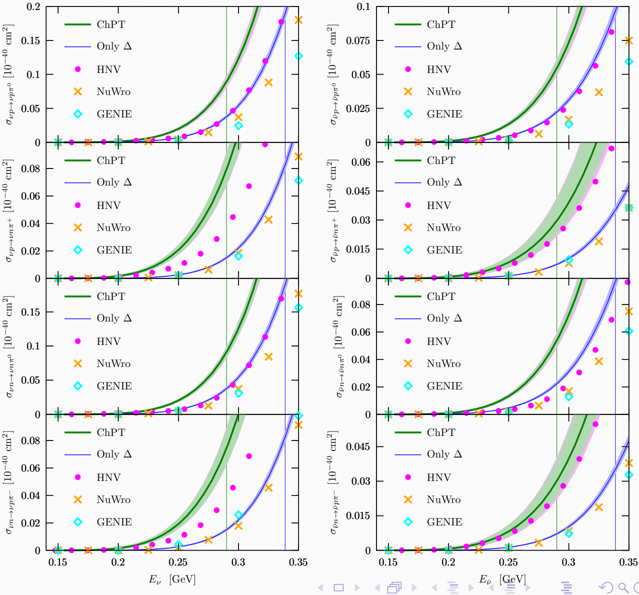
Cross sections for CC1π

- Order by order
  - Quite significant contribution when stepping from $O(p^2)$ and $O(p^3)$
  - Next-order effects could still be relevant (especially loops that πN can be put on-shell)



Cross sections for NC1π

- The $O(p^3)$ ChPT calculation produces considerably larger cross sections with respect to the HNV model in all reaction channels
- Nuwro and GIENE results agree with the ChPT ones with Δ contribution
- Non-resonant contribution is sizeable, not accounted by Nuwro and GIENE



Summary and outlook

- **Systematically study the weak single pion production off the nucleon for the first time within covariant BChPT up to $O(p^3)$ with explicit Δs**
  - The Δ-mechanism contributes significantly to all production channels
  - NC1π: Non-resonant contribution is sizeable which is not implemented in events generators like NuWro and GIENE
  - Provide a well-founded low energy benchmark for phenomenological models aimed at the description of weak pion production in the broad kinematic range of interest for current and future neutrino-oscillation expriments
- **Future application and improvement**
  - Applied to study various low-energy theorems
  - Applied to study electro-pion production for which there exists a wealth of experimental data and more LECs can be determined
  - etc

Thank you very much for your attention!