Electro-weak π production off nucleons near threshold in ChPT

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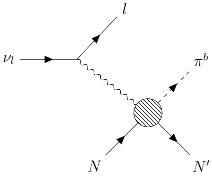
Overview

- In the study of neutrino properties, the ν interaction with matter is of interest.
- We want to properly describe neutrino-nucleon(nucleus) interaction
- Precision is required at the hadron level in the low energy regime
- In particular, our aim is to determine with precision the neutrino-induced π production on nucleons

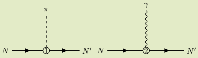


Motivation : What can different hadronic processes do for neutrino-nucleon interactions ?

We can study this by extracting *COMMON* relevant *parameters* in a common model with other reactions and quantities and using available experimental data

For example : π-N scattering, nucleon magnetic moments, axial charge (Fitting model from exp.data)

$$\pi N \to \pi N,$$



$\cdots$

Pion Photoproduction (Fitting model from exp.data)

$$\gamma + N \to \pi + N'$$

Pion Electro-production (Fitting model from exp.data)

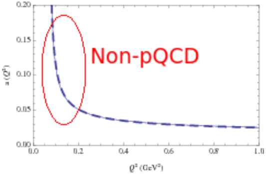
$$e + N \to e + \pi + N'$$

Weak Pion production–> Neutrino high precision processes (Predictions : Extracted information from above processes)

$$\nu_l + N \to N' + \pi + l(\nu_l)$$

How ca be approached ? : Non perturbative QCD

Energy regions for strong coupling α_S

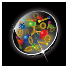


NON-PERTURBATIVE REGIME

- Low energy regime
- $E_\gamma \approx 145$ MeV - 215 MeV $\Longrightarrow$ $\alpha_S >> 1GeV$ perturbative QCD breakdown

We need an Effective Theory approach $\Longrightarrow$ **Chiral Perturbation Theory**.

- At low energies : ~~Quarks and Gluons~~ $\Longrightarrow$ Baryons and Mesons



$\Longrightarrow$

- We have **small** expansion parameters : ~~Strong coupling α_S~~ $\Longrightarrow$ small relative momenta $\frac{p}{\Lambda_{QCD}}$ and pion mass $\frac{m_\pi}{\Lambda_{QCD}}$
- At low energies leading interaction contants are introduced $\Longrightarrow$ Low-Energy-Constants (LECs)

Chiral Perturbation Theory (Hadronic degrees of freedom)

Lagrangian based on the QCD symmetries

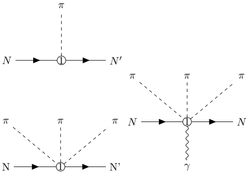
Each chiral order brings new LECs with it.

$$\mathcal{L}_N^{(1)} = \bar{\Psi}\left(i\not{D} - m + \frac{g}{2}\not{u}\gamma_5\right)\Psi,$$

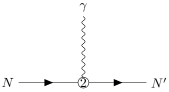
$$\mathcal{L}_N^{(2)} = \bar{\Psi}\frac{1}{8m}\left(c_6 F^+_{\mu\nu} + c_7 \mathrm{Tr}\left[F^+_{\mu\nu}\right]\right)\sigma^{\mu\nu}\Psi + \cdots,$$

$$\mathcal{L}_N^{(3)} = \bar{\Psi}\frac{i\epsilon^{\mu\nu\alpha\beta}}{2m}\left[d_8 \mathrm{Tr}\left[\widetilde{F}^+_{\mu\nu}u_\alpha\right] + d_9 \mathrm{Tr}\left[F^+_{\mu\nu}\right]u_\alpha + \mathrm{h.c.}\right]D_\beta\Psi + \cdots$$

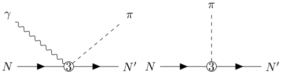
$O(p^1) : g_A$



$O(p^2) : c_6, c_7$



$O(p^3) : d_8, d_9, d_{16}, d_{18}, d_{20}, d_{21}, d_{22}$

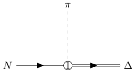


Theoretical Approach at intermediate energy

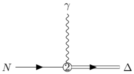
We have learned from EM induced π production that Δmechanism is crucial even close to threshold to properly reproduce the data

$$\mathcal{L}^{(1)}_{\Delta\pi N} = \frac{i h_A}{2 F m_\Delta} \bar{\Psi} T^a \gamma^{\mu\nu\lambda} (\partial_\mu \Delta_\nu) \partial_\lambda \pi^a + \text{h.c.},$$

$$\mathcal{L}^{(2)}_{\Delta\gamma N} = \frac{3 i e g_M}{2m(m+m_\Delta)} \bar{\Psi} T^3 (\partial_\mu \Delta_\nu) \tilde{f}^{\mu\nu} + \text{h.c.},$$



h_A related to Γ_Δ^{strong}

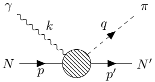


g_M related to Γ_Δ^{EM}

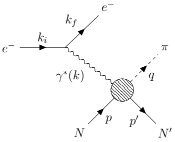
Physical channels

Photo- electro induced π-production

Photoproduction



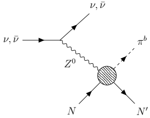
Electroproduction
(One photon-exchange approximation)



$$\begin{array}{ll} \gamma^{(*)} + p \to \pi^0 + p & g, m, F, c_1, c_6, c_7 \\ \gamma^{(*)} + p \to \pi^+ + n & d_6, d_7, d_8, d_9, d_{16} \\ \gamma^{(*)} + n \to \pi^- + p & d_{18}, d_{20}, d_{21}, d_{22} \\ \gamma^{(*)} + n \to \pi^0 + n & l_6, g_M, h_A \end{array}$$

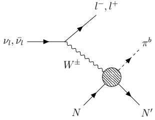
Neutrino induced π production

NC weak production



$$\begin{array}{ll} Z^0 + p \to \pi^0 + p & g, m, F, c_1, c_2, c_3, c_4, \\ Z^0 + p \to \pi^+ + n & c_6, c_7, d_1, d_2, d_3, d_5, \\ Z^0 + n \to \pi^- + p & d_6, d_7, d_8, d_9, d_{14}, \\ Z^0 + n \to \pi^0 + n & d_{15}, d_{18}, d_{20}, d_{21}, \\ & d_{22}, d_{23}, l_6, h_A \end{array}$$

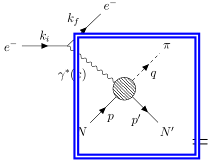
CC weak production



$g,$

$$\begin{array}{ll} W^+ + p \to \pi^+ + p, & W^- + n \to \pi^- + n \\ W^+ + n \to \pi^+ + n, & W^- + n \to \pi^0 + n \\ W^+ + n \to \pi^0 + p, & W^- + n \to \pi^- + n \end{array}$$

Amplitude structure for the EM process

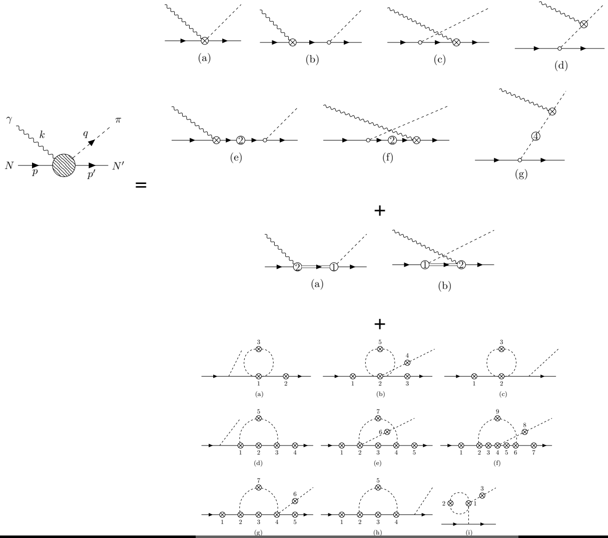


$$= \underbrace{ie\bar{u}(k_f, s_f)\gamma^\nu u(k_i, s_i)}_{\text{Lepton vertex}} \underbrace{\left(i\frac{-g_{\mu\nu}}{k^2 + i\epsilon} + \cdots\right)}_{\text{Virtual photon propagator}} \underbrace{\left(-ie\langle N'\pi|J^\mu(0)|N\rangle\right)}_{\text{Hadron vertex}}$$

$$= \epsilon_\mu \mathcal{H}^\mu$$

Hadronic amplitudes

- Using all the ingredients, we calculate all possible diagrams up to $O(p^3)$ order



In short words : Which are the relevant LECs ?

$$\begin{aligned}\mathcal{L}_{\text{ChPT}} =& \mathcal{L}_N^{(1)}(m_0, g_0) + \mathcal{L}_N^{(2)}(c_1, c_6, c_7) + \mathcal{L}_N^{(3)}(d_6, d_7, d_8, d_9, d_{16}, d_{18}, d_{20}, d_{21}, d_{22}) \\ &+ \mathcal{L}_{\pi\pi}^{(2)}(F_0, M_0) + \mathcal{L}_{\pi\pi}^{GSS(4)}(l_3, l_4, l_6) + \cdots\end{aligned}$$

$\Downarrow$ Hadron amplitude calculation

$$\begin{aligned}\mathcal{H}^\mu =& \sqrt{\mathcal{Z}_\pi}\mathcal{Z}_N \Big[\mathcal{M}_{tree}^{\mu(1)}(m_N, g_A, F_\pi, M_\pi) \\ &+ \mathcal{M}_{tree}^{\mu(2)}(\widetilde{c}_6, \widetilde{c}_7) + \mathcal{M}_{\Delta}^{\mu(5/2)}(h_A, g_M) \\ &+ \mathcal{M}_{tree}^{\mu(3)}(d_6, d_7, d_8, d_9, d_{18}, d_{20}, d_{21}, d_{22}, l_6) \\ &+ \widetilde{\mathcal{M}}_{loop}^{\mu(3)} + \mathcal{O}(p^4)\Big]\end{aligned}$$

- **Only d_8, d_9, d_{20}, d_{21}, d_{22} free parameters to be determined**

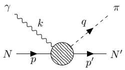
Inputs

Fitted LECs from other works using the same approach

TABLE – Values of the LECs determined from other processes.

	LEC	Value	Source
$\mathcal{L}_N^{(2)}$	$\widetilde{c}_6$	5.07 ± 0.15	μ_p and μ_n [Bauer :2012,Yao :2018,PDG]
	$\widetilde{c}_7$	-2.68 ± 0.08	
$\mathcal{L}_N^{(3)}$	d_6	-0.70 GeV^{-2}	N EM Form factor [Fuchs :2003]
	d_7	-0.49 GeV^{-2}	
	d_{18}	-0.02 ± 0.08 GeV^{-2}	πN scattering [Alarcon :2012]
$\mathcal{L}_{\pi\pi}^{(4)}$	l_6	$(-1.34 \pm 0.12) \times 10^{-2}$	$\langle r^2 \rangle_\pi$ [Yao :2018]
$\mathcal{L}_{\Delta N\pi}^{(1)}$	h_A	2.87 ± 0.03	$\Gamma_\Delta^{\mathrm{strong}}$ [Bernard :2012]
$\mathcal{L}_{\Delta N\gamma}^{(2)}$	g_M	3.16 ± 0.16	$\Gamma_\Delta^{\mathrm{EM}}$ [Blin :2015]

- We fit few LECs appearing in $\gamma(*)N \to \pi N'$

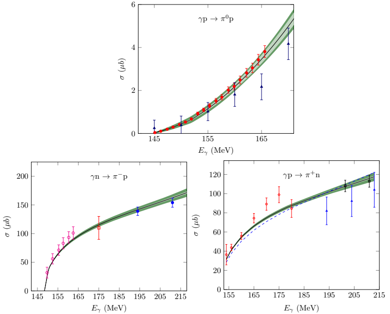


$d_8, d_9, d_{20}, d_{21}, d_{22}$

DATA from EM processes

$$\chi^2 = \sum_i \frac{(data - theory(d_j))^2}{(error\ data)^2}$$ minimization

Photoproduction ~ 1917 data points...



far more data ...

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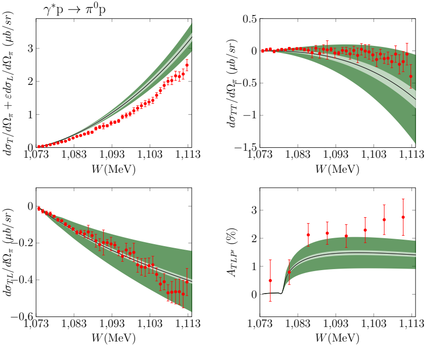
Electroproduction ~ 769 data points ...



far more data ...

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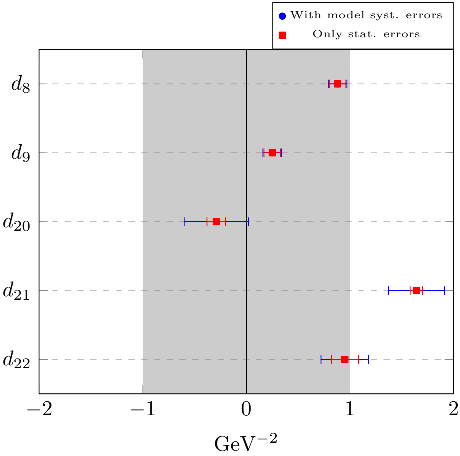
Output : LEC fit with $\gamma(^*) + N \to \pi + N'$ data

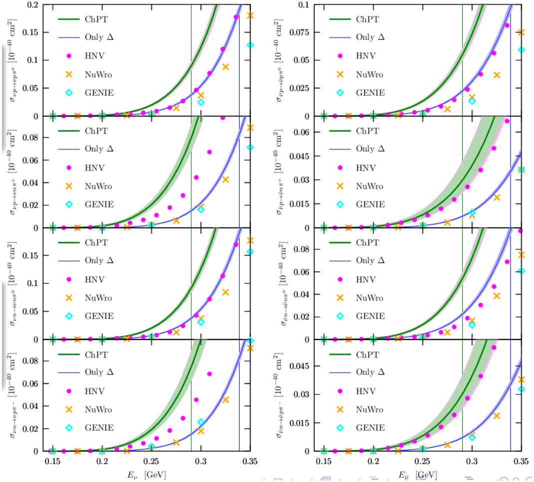


$\Rightarrow$ Intended to use as INPUT $\{d_8, d_9, d_{20}, d_{21}, d_{22}\}$ for $\nu + N \to \pi + l(\nu_l) + N'$ reactions

cross sections for NC1π

The previously unknown LECs $\rightarrow$ set to natural size :

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



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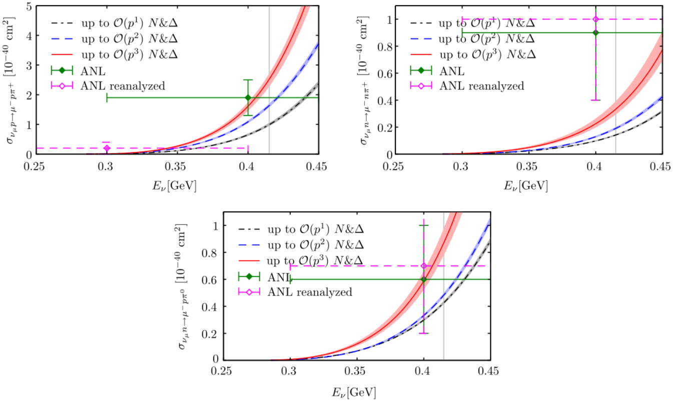
cross sections for CC1π

The previously unknown LECs $\rightarrow$ set to natural size :

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



Phys.Rev.D 98 (2018) 7, 076004

Conclusions

- ChPT 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 experiments.
- The Δ-mechanism contributes significantly in all π-N production processes.
- Estimation of the errors at the ν-nucleon interaction level are expected to be smaller at low energy.
- Applied to study neutrino interactions in nuclear medium.

Thank you

Fits

TABLE – The values of the LECs are dimensionless for g_M, in units of GeV^{-2} for d's. Fit I refers to the standard setting, Fit III includes non-fitting LEC errors

LECs	Fit-I	Fit-II	Fit-III
$d_8 + d_9$	1.12 ± 0.01	1.12 ± 0.02	0.89 ± 0.14
$d_8 - d_9$	0.63 ± 0.15	0.64 ± 0.10	0.26 ± 0.24
d_{20}	-0.29 ± 0.09	-0.29 ± 0.31	-0.03 ± 0.34
d_{21}	1.64 ± 0.06	1.64 ± 0.27	1.38 ± 0.30
d_{22}	0.95 ± 0.13	0.95 ± 0.23	0.99 ± 0.23
g_M	2.90 ± 0.01	$\mathbf{2.90 \pm 0.01}$	$\mathbf{3.16 \pm 0.16}$
χ^2/dof	$\mathbf{2.7}$	$\mathbf{2.9}\pm$	$\mathbf{3.2 \pm 0.2}$