Global analysis of the $\Delta(1232)$ contribution in the pion photo-production on nucleons

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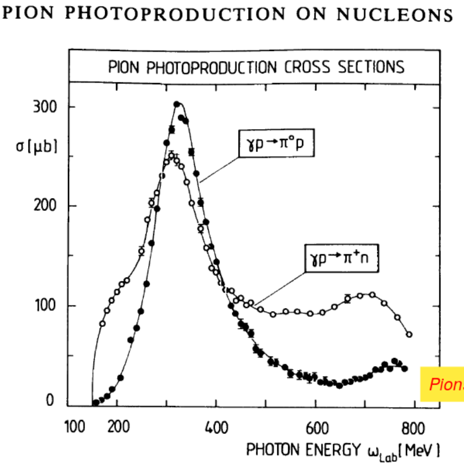
Collaboration: Manuel J. Vicente Vacas,
Astrid H. Blin,
Deliang Yao.

Outline

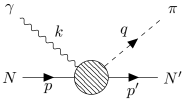
Motivation



- At the peak the neutral channel has bigger cross section than the charged channel
- Near threshold there are huge cancellations for the neutral channel (not well described at low energy)
- For the charged channel there are not such cancellations
- How much contributes the resonances at low energies for neutral and charged channels ?
- We want to know how to deal properly with this energy region

Pions and Nuclei, Ericson & Weise

Experimental data



$E_\gamma \sim 145$ MeV - ~ 215 MeV

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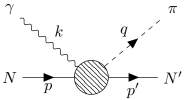

$\gamma p \to \pi^0 p$

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Measured observables :

$$\sigma \quad , \quad \frac{d\sigma}{d\Omega} \quad , \quad \Sigma = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}, \quad T = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-}$$

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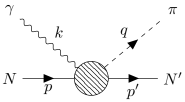

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779 data points

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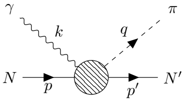

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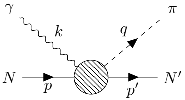

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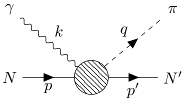

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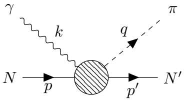

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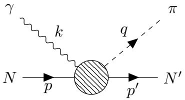

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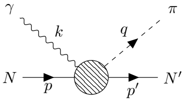

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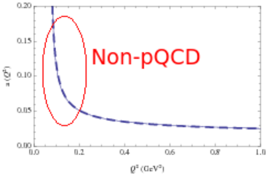
Nothing yet
0 data points

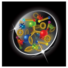
Approaching the experimental data



NON-PERTURBATIVE REGIME

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

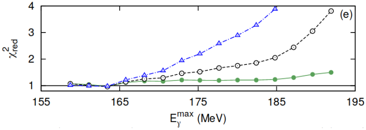
  We need an Effective Theory approach $\Longrightarrow$ **Chiral Perturbation Theory**.
- At low energies : Relevant degrees of freedom



$\Longrightarrow$

- We use as expansion parameters the relative $\frac{p}{\Lambda}$ and pion mass $\frac{m_\pi}{\Lambda}$

Previous works : Theoretical models for $\gamma p \to \pi^0 p$



$O(p^4)$ relativistic ChPT
$O(p^4)$ HBChPT
Empirical fit

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Starts failing at 20 MeV above π threshold

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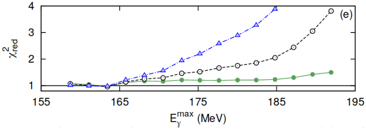

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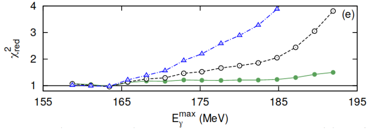

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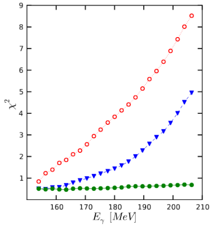
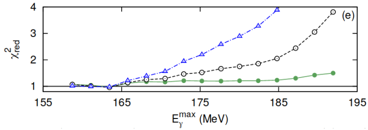


- $O(p^3)$ relativistic [tree level] ChPT
- $O(p^3)$ relativistic [tree+loops] ChPT
- relativistic [tree+loops+Δ] H. Blin et al. PLB(2015)

Some problems : Theoretical models for $\gamma p \to \pi^0 p$



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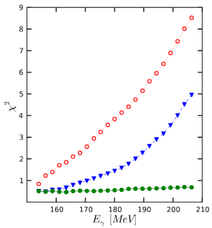


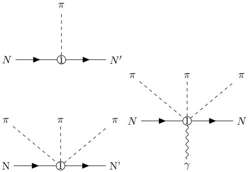
- Our aim is to extend this framework, relativistic ChPT with explicitly $\Delta(1232)$ inclusion,to the charged channels making a global analysis

The nucleon Lagrangian

Each chiral order brings new LECs with it. For this process $\gamma N \to \pi N'$

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

$O(p^1) : g_A$



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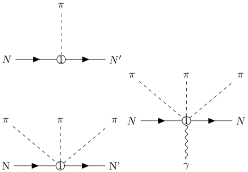
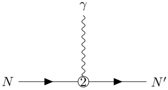


$O(p^2) : c_6, c_7$



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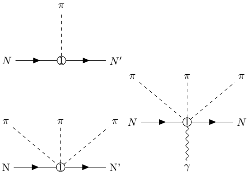
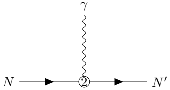
$$\mathcal{L}_N^{(3)} = \bar{\Psi}\frac{i\epsilon^{\mu\nu\alpha\beta}}{2m}\left[d_8 \mathrm{Tr}\left[\widetilde{F}^+_{\mu\nu}u_\alpha\right] + d_9 \mathrm{Tr}\left[F^+_{\mu\nu}\right]u_\alpha + \text{h.c.}\right]D_\beta\Psi$$
$$+ \bar{\Psi}\frac{\gamma^\mu\gamma_5}{2}\left[d_{16}\mathrm{Tr}\left[\chi_+\right]u_\mu + d_{18}\, i[D_\mu,\chi_-]\right]\Psi + d_{20}\bar{\Psi}\left[-i\frac{\gamma^\mu\gamma_5}{8m^2}[\widetilde{F}^+_{\mu\nu},u_\lambda]D^{\lambda\nu} + \text{h.c.}\right]\Psi$$
$$+ d_{21}\bar{\Psi}\left[\frac{1}{2}i\gamma^\mu\gamma_5[\widetilde{F}^+_{\mu\nu},u^\nu]\right]\Psi + d_{22}\bar{\Psi}\left[\frac{1}{2}\gamma^\mu\gamma_5[D^\nu,F^-_{\mu\nu}]\right]\Psi + \cdots$$

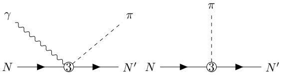
$O(p^1): g_A$



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



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

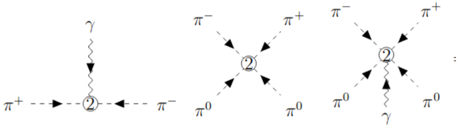


The pion Lagrangian

Up to $O(p^3)$ we do not need extra fitting Low-Energy-Constants

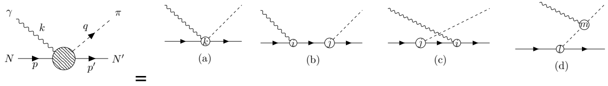
$$\mathcal{L}_{\pi\pi}^{(2)} = \frac{F_\pi^2}{4} \mathrm{Tr}\left[D^\mu U \left(D_\mu U\right)^\dagger + \chi U^\dagger + U \chi^\dagger \right].$$

All can be expanded in terms of no fitting parameters



Putting the pieces together

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



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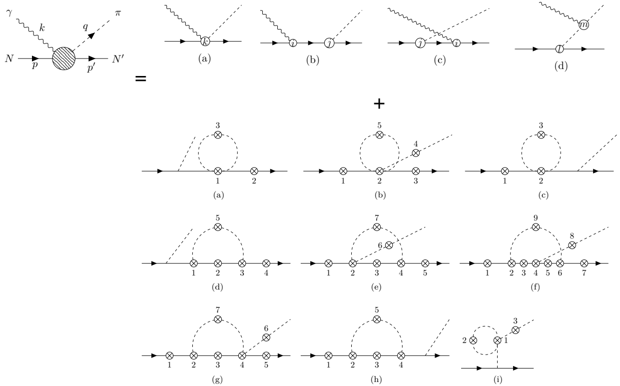

- This approach is the same as used in previous ChPT works

The Strategy

- We keep our expansion up to $O(p^3)$: Avoids inclusion of too many LECs at $O(p^4)$

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Loop diagrams regularization

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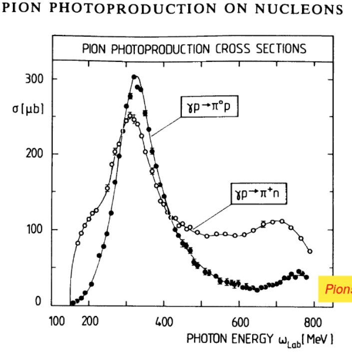
Loop diagrams regularization

- Loop diagrams : UV divergences and power counting breaking terms

$\frac{1}{\epsilon_{UV}} = \frac{1}{4-dim}$ and terms $\propto p^1$, p^2, in amplitudes at order $O(p^3)$

- Renormalization $\widetilde{\text{MS}}$-EOMS :
  - $\widetilde{\text{MS}}$: Substracts multiples of $R = \gamma_E - 1/\epsilon_{UV} - \log(4\pi) - 1,$
  - EOMS : Substracts terms of lower order than the nominal one for loop diagrams

The Strategy to improve the approach



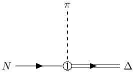
Pions and Nuclei, Ericson & Weise

- Explicit inclusion of the $\Delta(1232)$ spin $3/2$ resonance
- $\Delta(1232)$ becomes more relevant the closer we are to its mass
- $\Delta(1232)$ inclusion is important in charged and neutral channels
- No more Low-Energy-Constants to be fitted (keep the model simple)

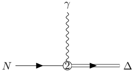
Contributions generated by the $\Delta(1232)$

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

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



h_A related to Γ_Δ^{strong}



g_M related to Γ_Δ^{EM}

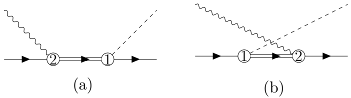
Only one constrained parameter added, $g_M h_A$

Power Counting Scheme

- For energies close to threshold, far from the $\Delta(1232)$ mass :
  Lensky & Pascalutsa EPJ (2010)

$$D = 4L + \sum_{k=1}^{\infty} kV^{(k)} - 2N_\pi - N_N - \frac{1}{2}N_\Delta .$$

- No loop diagrams with $\Delta(1232)$ up to $O(p^3)$.



- $\Delta(1232)$ is only included at tree level —> $O(p^{5/2})$ order

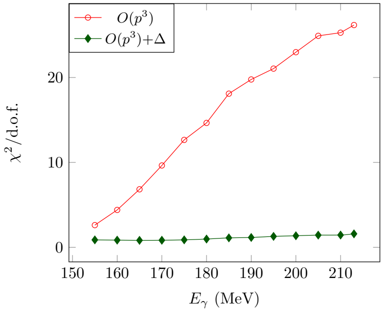
The first message

Fitting LECs using data for all channels

The first message

Fitting LECs using data for all channels

Now we can see easily what can be obtained with the $\Delta(1232)$ inclusion, **without including extra fitting Low-Energy-Constants**



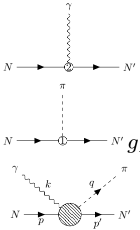
- ChPT up to $O(p^3)$ with loops
- ChPT up to $O(p^3)$ with loops & $\Delta(1232)$ inclusion

What about low-energy constants ?

Fitted LECs from other works using the same approach

	LEC	Source
$\mathcal{L}_N^{(2)}$	$\tilde{c}_6$ $\tilde{c}_7$	μ_p & μ_n [Bauer 2012],[Fuchs 2004]
$\mathcal{L}_N^{(3)}$	d_{16}^r	g_A [Yao 2017]
	d_{18}^r	πN scattering [Alarcon, 2012]
	d_{22}^r	$\langle r_A^2 \rangle_N$ [Yao 2017]
$\mathcal{L}_{\pi N\Delta}^{(1)}$	h_A	$\Gamma_\Delta^{\mathrm{Strong}}$ [Bernard, PRD(2013)]
$\mathcal{L}_{\pi N\Delta}^{(2)}$	g_M	$\Gamma_\Delta^{\mathrm{em}}$ [Blin 2015]

- c_6 and c_7 directly connected to nucleon magnetic moments
- d_{16}, related to the πN axial-vector coupling, g_A
- d_{18}, studied in πN scattering processes (Golderberg-Treiman relation in πN coupling)
- We can fit few LECs appearing in $\gamma N \to \pi N'$



c_6, c_7

$g_A, d_{16}, d_{18},$

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

Preliminary results

TABLE – LECs and χ^2 for calculations at different chiral orders. Bold numbers are fixed and depend only on physical quantities such as g_A, the proton and neutron magnetic moment and the Δ decay width. Thus, they are not fitted to the pion photoproduction process.

LECs	$O(p^1)$	$O(p^2)$	$O(p^{5/2})$	$O(p^3)$, Fit I
g	$\mathbf{1.27}$	$\mathbf{1.27}$	$\mathbf{1.27}$	$\mathbf{1.11}$
c_6	-	$\mathbf{3.706}$	$\mathbf{3.706}$	$\mathbf{5.07}$
c_7	-	$\mathbf{-1.913}$	$\mathbf{-1.913}$	$\mathbf{-2.68}$
d_{18}	-	-	-	$\mathbf{0.60}$
d_{22}	-	-	-	$\mathbf{0.96}$
$d_8 + d_9$	-	-	-	1.16 ± 0.01
$d_8 - d_9$	-	-	-	1.02 ± 0.13
d_{20}	-	-	-	14.9 ± 2.5
d_{21}	-	-	-	-2.65 ± 0.18
h_A	-	-	$\mathbf{2.87}$	$\mathbf{2.87}$
g_M	-	-	$\mathbf{3.16}$	2.90 ± 0.01
χ^2_{TOT}/dof	**165.**	**310.**	**60.7**	**3.25**
$\chi^2_{\pi 0}/dof$	208.	392.	76.6	3.58
$\chi^2_{\pi +}/dof$	10.7	9.15	2.88	1.76
$\chi^2_{\pi -}/dof$	5.73	6.29	2.51	2.49

Preliminary results

TABLE – The values of the LECs are dimensionless for g_M, in units of GeV^{-2} for d's, and in units of GeV^{-3} for e_{48}. Fit I refers to the standard setting, Fit II removes Δ mechanisms, Fit III leaves d_{18} free and Fit IV includes an $O(p^4)$ piece (e_{48})

LECs	Fit I	Fit II - $\not\Delta$	Fit III	Fit IV
$d_8 + d_9$	1.16 ± 0.01	3.53 ± 0.01	0.98 ± 0.02	0.90 ± 0.01
$d_8 - d_9$	1.02 ± 0.14	1.84 ± 0.24	1.72 ± 0.13	-0.09 ± 0.15
d_{18}	$\mathbf{0.60}$	$\mathbf{-1.00}$	5.40 ± 0.13!!	$\mathbf{0.60}$
d_{20}	14.9 ± 2.5	-17.6 ± 2.4	29.7 ± 2.6	6.94 ± 2.5
d_{21}	-2.65 ± 0.18	0.01 ± 0.17	-1.52 ± 0.19	-2.46 ± 0.18
g_M	2.90 ± 0.01	-	3.13 ± 0.02	3.20 ± 0.01
e_{48}	-	-	-	1.97 ± 0.04
χ^2_{TOT}/dof	**3.25**	**30.0**	**1.59**	**1.58**
$\chi^2_{\pi^0}/dof$	3.58	37.2	1.33	1.48
$\chi^2_{\pi^+}/dof$	1.76	3.66	2.40	1.67
$\chi^2_{\pi^-}/dof$	2.49	4.95	2.69	2.40

- c_6, c_7 LECS are fixed from nucleon form factors (μ_p,μ_n) (When they are included in the fit we get the same value, with or without Δ)
- $d's$ LECs are sensitive to the lower order corrections, i.e., to the Δ inclusion.
- d_{18} Goldelberg-Treiman relation, leads backward angles at lower energies.
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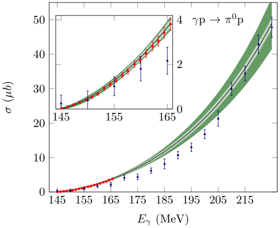
Comparing theoretical results vs experimental data

Cross sections



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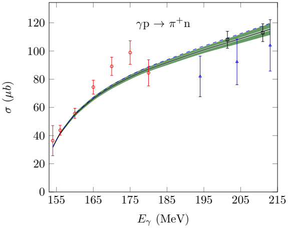

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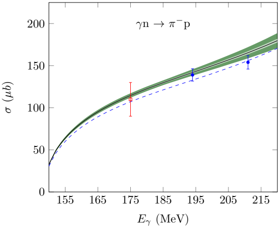

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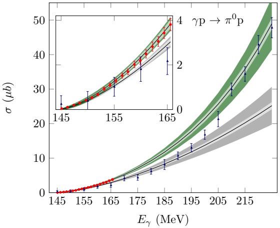

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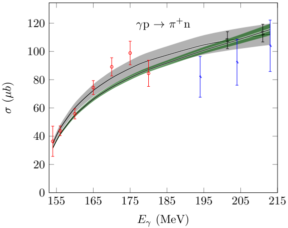

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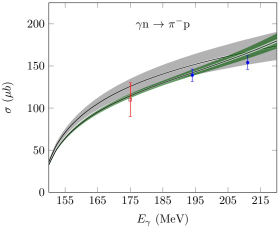

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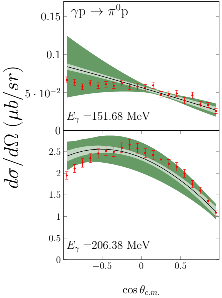
Angular cross sections



- Hornidge et al., (MAMI) PRL (2013)
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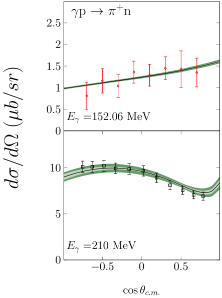

- E. Korkmaz et al., PRL (1999)
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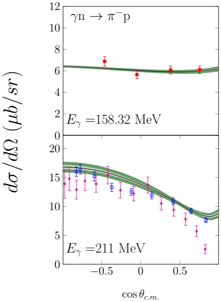

- K. Liu, Ph. D. thesis, University of Kentucky (1994)
- V. Rossi et al., NCA (1973)
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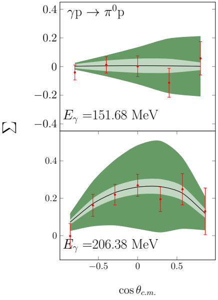
Beam asymmetries



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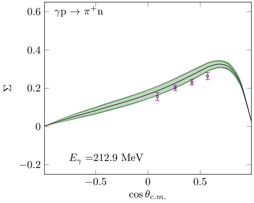

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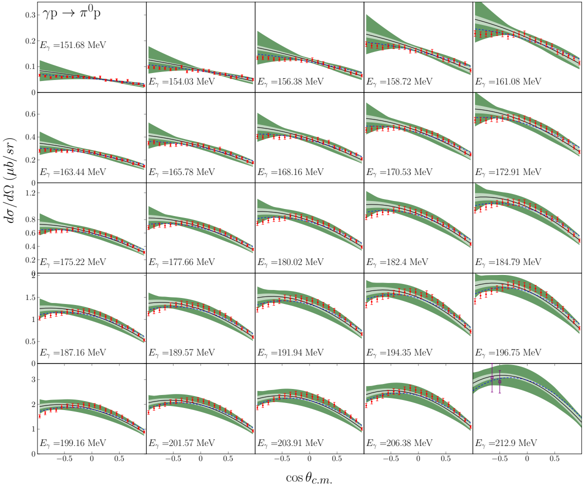
Differential cross sections



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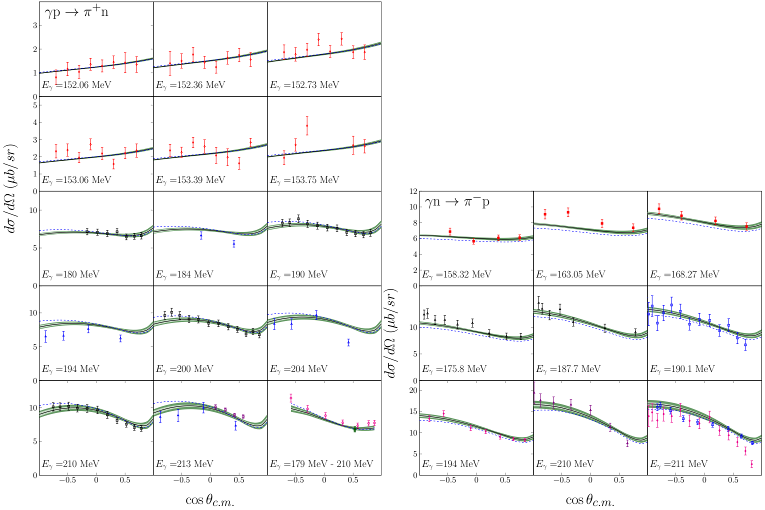

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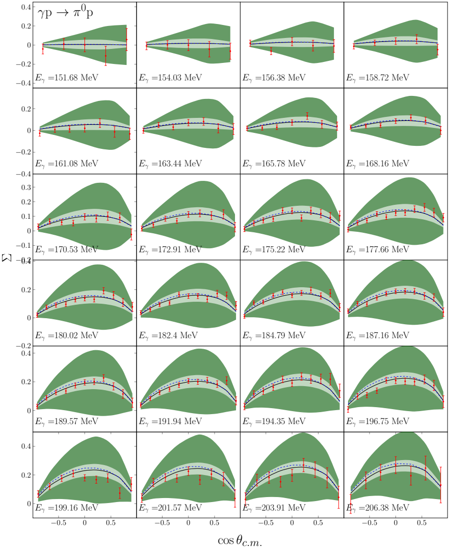
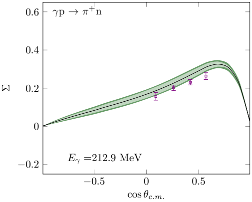
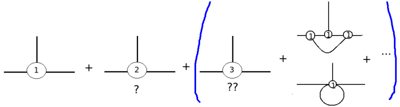




What is the next ?

- Other reactions :
  π-electro-production off nucleons $\gamma^* N \to \pi N'$
- Trying to simplify the model by the $\Delta(1232)$ inclusion. No need to reach higher orders at this energy (This would add many unknown LECs)
- Increase the prediction capability and useful accuracy of this approach for other processes



Fit LECs for first $\to$ then make predictions for other processes

Other processes in the same framework ?

Nucleon magnetic moments and Δ EM decays

$$N \to N'\gamma, \quad \Delta \to N\gamma$$

Pion Photoproduction (Prediction/LECs Fitting)

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

$\chi^2/dof = 3.25$ with Δ, $\chi^2/dof = 30.0$ $\not\Delta$

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$$eN \to \pi N'$$

Weak Pion production–> Neutrino high precision processes (Predictions)

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- Globally the Δ inclusion improves much the agreement between data and ChPT models, even without extra fitting constants.
- Wider agreement with data near Δ mass using $O(p^3)$ calculation with Δ inclusion than previous higher order $O(p^4)$ calculation without Δ.
- Even the inclusion of asingle tree level order $O(p^4)$ piece can improve the results being good enough as a full $O(p^4)$ calculation can do with many paramateres.

Thank you

Error estimations

$$\delta\mathcal{O}_{LEC} = \left(\sum_{i,j}[\text{Corr}(i,j)]\,\frac{\partial\mathcal{O}(\bar{x}_i)}{\partial x_i}\delta x_i\frac{\partial\mathcal{O}(\bar{x}_j)}{\partial x_j}\delta x_j\right)^{1/2},$$

$$\delta\mathcal{O}_{th}^{(n)} = \text{max}\left(\left|\mathcal{O}^{(n_{LO})}\right|Q^{n-n_{LO}+1},\left\{\left|\mathcal{O}^{(k)}-\mathcal{O}^{(j)}\right|Q^{n-j}\right\}\right),\quad n_{LO}\leq j\leq k\leq n$$

where $Q = m_\pi/\Lambda_b$, Λ_b is the breakdown scale of the chiral expansion. We have $\Lambda_b = 4\pi F_\pi \sim 1$ GeV.

Other fitted LECs

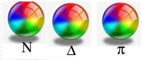
TABLE – Values of the LECs determined from other processes.

	LEC	Value	Source
$\mathcal{L}_N^{(2)}$	$\tilde{c}_6$	5.07 ± 0.15	μ_p and μ_n [Bauer :2012pv,Yao :2018pzc,PDG :2016
	$\tilde{c}_7$	-2.68 ± 0.08	μ_p and μ_n [Bauer :2012pv,Yao :2019avf,PDG :2016
	d_{18}	-0.20 ± 0.80 GeV^{-2}	πN scattering [Alarcon :2012kn]
	d_{22}	5.20 ± 0.02 GeV^{-2}	$\langle r_A^2 \rangle_N$ [Yao :2017fym]
$\mathcal{L}_{\pi N\Delta}^{(1)}$	h_A	2.87 ± 0.03	$\Gamma_\Delta^{\mathrm{strong}}$ [Bernard :2012hb]
$\mathcal{L}_{\pi N\Delta}^{(2)}$	g_M	3.16 ± 0.16	$\Gamma_\Delta^{\mathrm{EM}}$ [Blin :2015era]

Chiral Perturbation Theory

χ PT

- At large distances (low energy) we are encouraged to use baryons and light mesons, instead of quarks and gluons, as degrees of freedom
- We use pion mass in the same spirit of the Chiral Symmetry Breaking in QCD with quark masses



- We use as expansion parameters the relative $\frac{p}{\Lambda}$ and pion mass $\frac{m_\pi}{\Lambda}$
- We can construct Lagrangians that preserves Chiral Symmetry for each order in expansion.
- Appears Low Energy Constants (should be extracted from QCD, but QCD cannot be solved)