Chiral dynamics in the $\gamma p \longrightarrow p\pi^0$ reaction at threshold

Astrid Hiller Blin

IFIC — CSIC — Universidad de Valencia
astrid.blin@ific.uv.es

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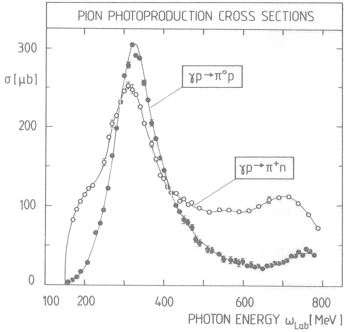
Co-authors:
Tim Ledwig
Manuel Vicente Vacas
PLB (2015), arXiv:1412.4083

Motivation

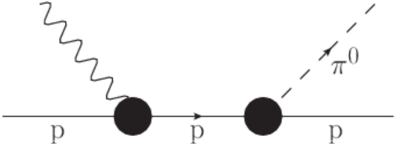
Ericson and Weise (1988) Pions and Nuclei



Reaction	Relative dipole moment
$\gamma p \to \pi^+ n$	1
$\gamma p \to \pi^0 p$	$-\frac{m_\pi}{m_N}$
$\gamma n \to \pi^- p$	$-\left(1+\frac{m_\pi}{m_N}\right)$
$\gamma n \to \pi^0 n$	0

- In the threshold region, the charged channels have much bigger cross sections than the neutral one.
- There are huge cancellations betweens pieces.
- The charged channels are well described in low-order ChPT. The neutral channel is NOT!

Experimental data



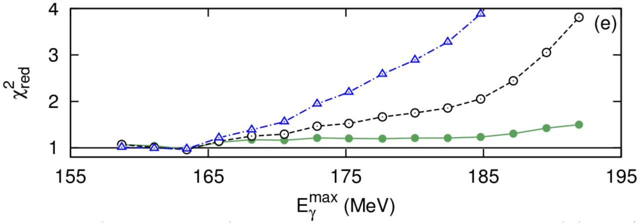
- New very precise data from MAMI. Hornidge et al. (2013) PRL
- Can be used to test the convergence of ChPT models.
- Measured polarization observables:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \quad \text{and} \quad \Sigma = \frac{\mathrm{d}\sigma_\perp - \mathrm{d}\sigma_\parallel}{\mathrm{d}\sigma_\perp + \mathrm{d}\sigma_\parallel}.$$

- Previous ChPT works have problems when approaching regions $> 20\mathrm{MeV}$ above threshold.

Previous works

$\mathcal{O}(p^4)$ ChPT: **HBChPT** and **covariant**. Hornidge et al. (2013) PRL



- Empirical fit.
- $\mathcal{O}(p^4)$ HBChPT.
- $\mathcal{O}(p^4)$ relativistic ChPT.

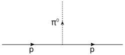
} Starts failing at 20 MeV above threshold.

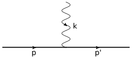
The nucleonic Lagrangian

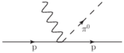
$$
\begin{aligned}
\mathcal{L}_N = \bar{\Psi}\Big\{ & \mathrm{i}\not{D} - m + \frac{g_A}{2}\not{u}\gamma_5 \\
& + \frac{1}{8m}\left(c_6 f^+_{\mu\nu} + c_7 \mathrm{Tr}\left[f^+_{\mu\nu}\right]\right)\sigma^{\mu\nu} \\
& + \frac{\mathrm{i}}{2m}\varepsilon^{\mu\nu\alpha\beta}\left(d_8 \mathrm{Tr}\left[\tilde{f}^+_{\mu\nu} u_\alpha\right] + d_9 \mathrm{Tr}\left[f^+_{\mu\nu}\right] u_\alpha + \text{h.c.}\right)\mathrm{D}_\beta \\
& + \frac{\gamma^\mu\gamma_5}{2}\left(d_{16}\mathrm{Tr}\left[\chi_+\right] u_\mu + \mathrm{i} d_{18}[\mathrm{D}_\mu, \chi_-]\right)\Big\}\Psi + \ldots
\end{aligned}
$$

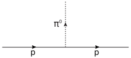
Fettes et al. (2000) Ann. Phys.

For this channel, one finds the following combinations of LECs:

- $\mathcal{O}(p^1)$ 

g_A
- $\mathcal{O}(p^2)$ 

c_{67}
- $\mathcal{O}(p^3)$ 

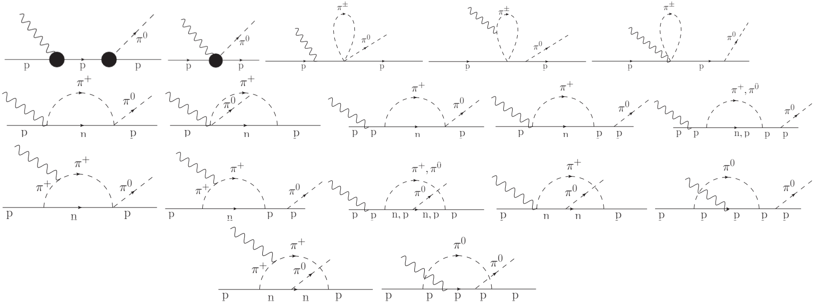
d_{89} 

d_{168}

See Hiller Blin et al. (2015) PLB, arXiv:1412.4083 for LECs definitions.

Putting the pieces together

- With these ingredients we calculate all possible nucleonic diagrams up to $\mathcal{O}(p^3)$.



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

Our strategy

- We stay at $\mathcal{O}(p^3)$ — avoids inclusion of too many LECs.
- The calculation of loop diagrams leads to divergences and power counting breaking terms $\Longrightarrow$ We use the EOMS-renormalization prescription.
  - It absorbs divergent terms of the type $L = \frac{2}{\epsilon} + \log(4\pi) - \gamma_E + 1$.
  - It also easily subtracts terms of lower order than the nominal order of a diagram.

Our strategy to improve the approach

- To reproduce the measured observables: Inclusion of the $\Delta(1232)$ isospin-3/2 resonance.
- More relevant the closer we are to its mass.
- Particularly important for neutral channel, as the lower orders have very small contributions. Hemmert et al. (1997) PLB

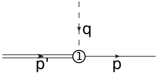
$$\mathcal{L}_\Delta = \bar{\Psi}\left\{\frac{ih_A}{2FM_\Delta} T^a \gamma^{\mu\nu\lambda}(\mathrm{D}^{ab}_\lambda \pi^a) + \frac{3e}{2m(m+M_\Delta)} T^3 \left(ig_M \tilde{F}^{\mu\nu} - g_E \gamma_5 F^{\mu\nu}\right) + \text{H.c.}\right\}\partial_\mu \Delta_\nu + \cdots$$

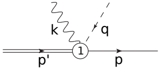
Pascalutsa and Philips (2003) PRC

Even more degrees of freedom?

Quite well-known LECs!

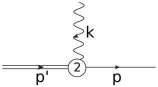
- $\mathcal{O}(p^1)$





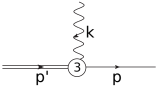
h_A

- $\mathcal{O}(p^2)$



g_M

- $\mathcal{O}(p^3)$



g_E

Power counting and divergences

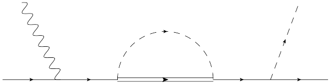
- The propagator is now a Rarita-Schwinger propagator:

$$\frac{\not{p} + M_\Delta}{p^2 - M_\Delta^2 + i\varepsilon}\left[-g^{\alpha\beta} + \frac{1}{D-1}\gamma^\alpha\gamma^\beta + \frac{1}{(D-1)M_\Delta}(\gamma^\alpha p^\beta - \gamma^\beta p^\alpha) + \frac{D-2}{(D-1)M_\Delta^2}p^\alpha p^\beta\right].$$

- Followed counting scheme (valid only for energies close to threshold and far from the $\Delta(1232)$ mass):

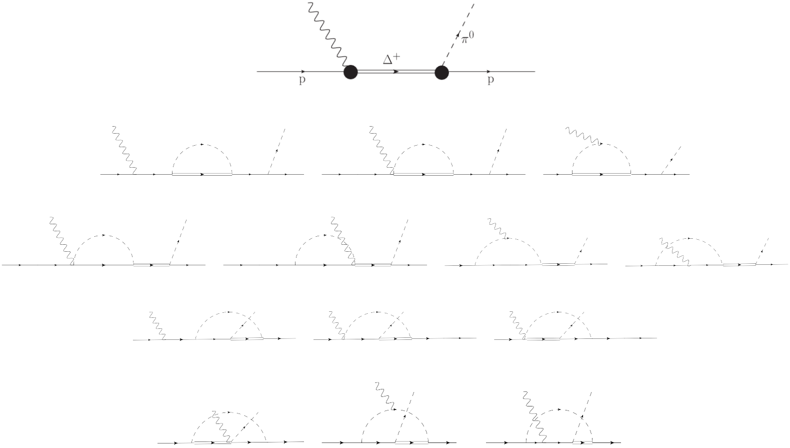
Pascalutsa and Philips (2003) PRC

$$D = 4L + \sum kV_k - 2N_\pi - N_N - \frac{1}{2}N_\Delta.$$

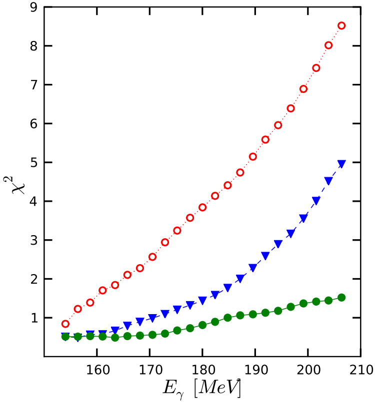


- The first set of Δ loop diagrams start only at $\mathcal{O}(p^{7/2})$.

Delta diagrams



Fitting low-energy constants

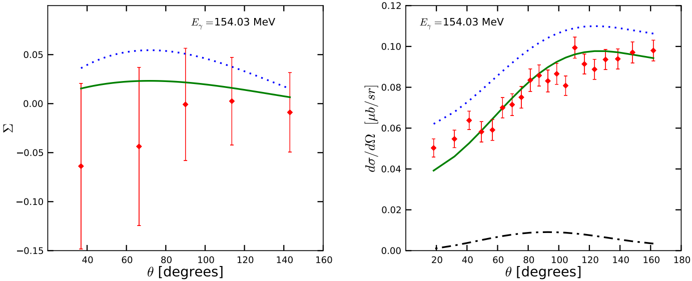


- Nucleonic tree level.
- Full nucleonic model up to $\mathcal{O}(p^3)$.
- Inclusion of $\Delta(1232)$ up to $\mathcal{O}(p^{3.5})$.

Preliminary results

	g_A	$\tilde{c}_{67}$	$\tilde{d}_{89}$ [GeV^{-2}]	$\tilde{d}_{168}$ [GeV^{-2}]	g_E	χ^2/d.o.f.
No Δ	1.46	2.86	4.20	-15.1	—	4.96
Full Model	**1.27**	2.64	1.19	-0.93	3.96	1.52

Comparing theoretical curves with data



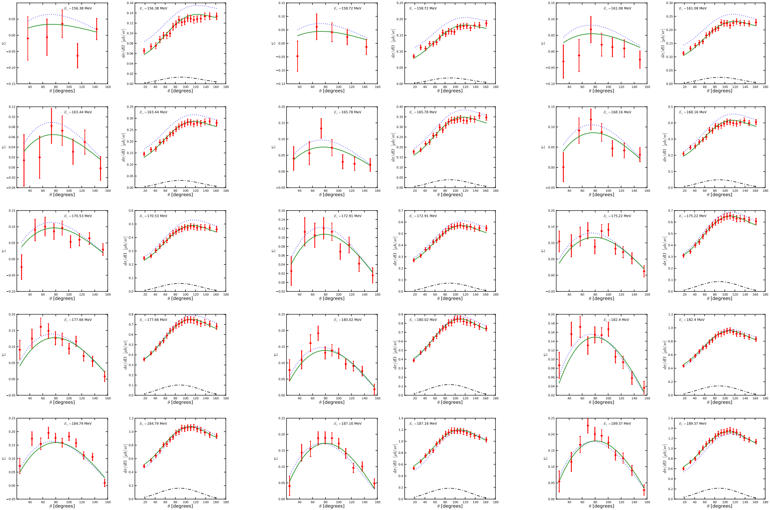
- Pion photoproduction data from MAMI: 800 data points!

  Hornidge et al. (2013) PRL
- Full nucleonic model up to $\mathcal{O}(p^3)$ Unable to reproduce the energy dependence
- $\Delta(1232)$ inclusion up to $\mathcal{O}(p^{3.5})$ Preliminary results
- $\Delta(1232)$ degrees of freedom only

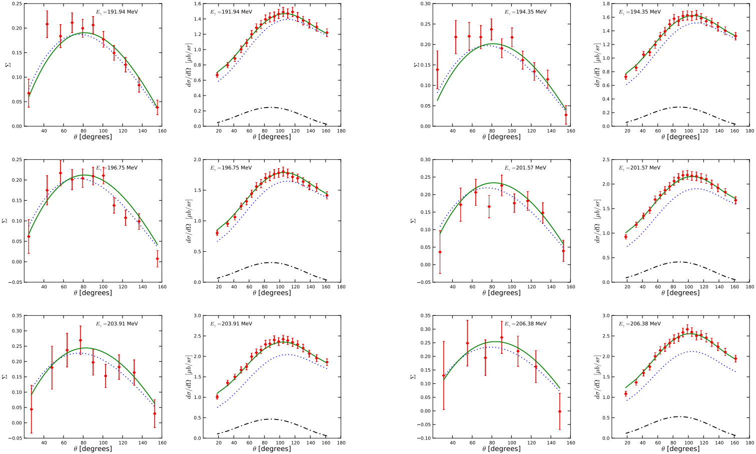
Well, everybody can reproduce threshold results!

What's the big deal?

Moving up to higher energies



And reaching regions above $200\mathrm{MeV}$...



Summary and outlook

- New pion photoproduction data shows that purely nucleonic ChPT models converge too slowly — even close to threshold.
- Including the $\Delta(1232)$ resonance strongly improves the accordance between data and ChPT models, even without bringing in new fitting constants.
- I showed you our preliminary results for the inclusion of Δ loop diagrams.
- We are finishing the study of the lowest multipoles E_0^+, E_1^+, M_1^+ and M_1^-.
- To have more information about the LECs, it would be necessary to extend these calculations to other channels.