Neutral pion photoproduction near threshold with chiral perturbation theory

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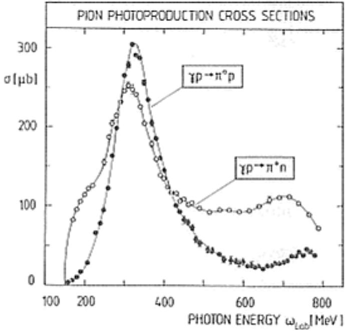
Motivation

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

Motivation

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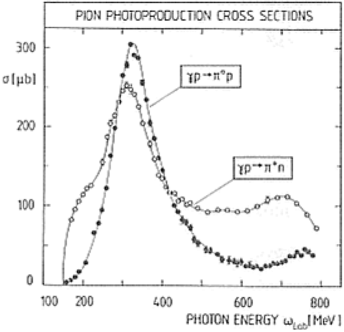
Ericson and Weise (1988) Pions and Nuclei

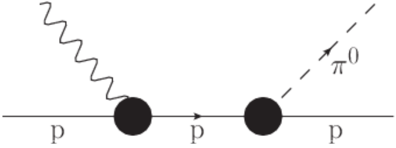


- Close to threshold:
  strong cancellations between amplitude pieces in neutral channel
- Charged channels well described in low-order ChPT. Neutral channels NOT

  Bernard et al. (1992) NPB
- The inclusion of the $\Delta(1232)$ spin-$3/2$ resonance is essential

  Hemmert et al. (1997) PLB

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

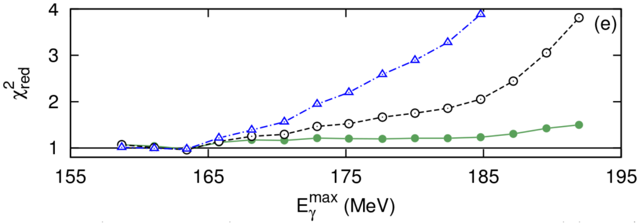


- Very precise data from MAMI Hornidge et al., Phys. Rev. Lett. 111 (2013) 062004
- Could be used to test the convergence of ChPT models
- Polarization observables measured:

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

Previous work

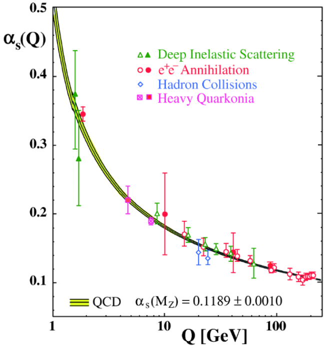
Hornidge et al., Phys. Rev. Lett. 111 (2013) 062004



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

} Starts failing at 20 MeV above threshold

Chiral perturbation theory

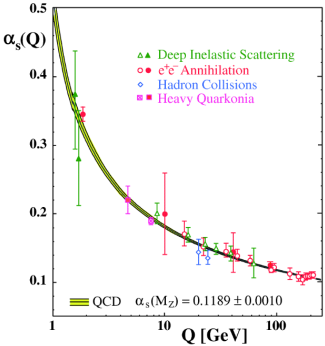


$$E_\gamma \approx \mathcal{O}(m_\pi) \Rightarrow \alpha_s = \mathcal{O}(1)$$

Perturbative QCD breaks down

$\Longrightarrow$ EFT: expansion around **other parameters**

Chiral perturbation theory



$$E_\gamma \approx \mathcal{O}(m_\pi) \Rightarrow \alpha_s = \mathcal{O}(1)$$

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$\Longrightarrow$ EFT: expansion around **other parameters**

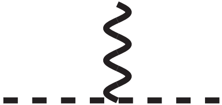
Chiral perturbation theory:

- Small masses, momenta ($\frac{m_\pi}{1\ \text{GeV}}, \frac{p_{\text{ext}}}{1\ \text{GeV}} \ll 1$): combined expansion
- New degrees of freedom: ~~quarks and gluons~~ $\Longrightarrow$ mesons and baryons

Chiral orders of the Lagrangian

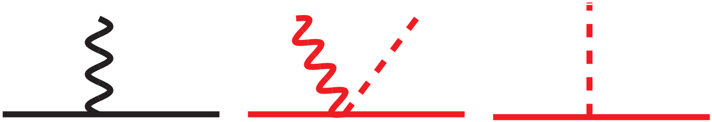
Lowest-order **pion** Lagrangian $\sim p_{\text{ext}}^2,\ m_\pi^2$

$$\mathcal{L}_\pi^{(2)} = \frac{F_0^2}{4}\mathrm{Tr}\left(\nabla_\mu U \nabla^\mu U^\dagger + \chi_+\right)$$



Lowest-order **nucleon** Lagrangian $\sim p_{\text{ext}}$

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

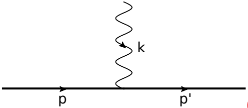


Higher-order terms

$$\mathcal{L}_N^{(2,3)} = \bar{N}\Big\{ \frac{1}{8m}\left(\mathbf{c_6} f^+_{\mu\nu} + \mathbf{c_7}\,\mathrm{Tr}\left[f^+_{\mu\nu}\right]\right)\sigma^{\mu\nu} + \frac{\mathrm{i}}{2m}\varepsilon^{\mu\nu\alpha\beta}\left(\mathbf{d_8}\,\mathrm{Tr}\left[\tilde{f}^+_{\mu\nu}u_\alpha\right] + \mathbf{d_9}\,\mathrm{Tr}\left[f^+_{\mu\nu}\right]u_\alpha + \mathrm{H.c.}\right)\mathrm{D}_\beta + \frac{\gamma^\mu\gamma_5}{2}\left(\mathbf{d_{16}}\,\mathrm{Tr}\left[\chi_+\right]u_\mu + \mathrm{i}\,\mathbf{d_{18}}[\mathrm{D}_\mu,\chi_-]\right)\Big\}N + \ldots$$

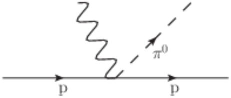
Fettes et al., Ann. Phys. 283 (2000) 273

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

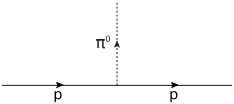


$\mathbf{c_6}$, $\mathbf{c_7}$

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

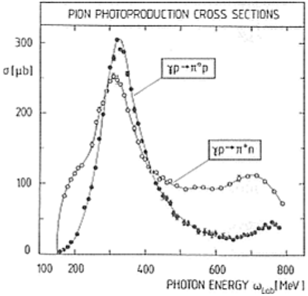


$\mathbf{d_8}$, $\mathbf{d_9}$



$\mathbf{d_{16}}$, $\mathbf{d_{18}}$

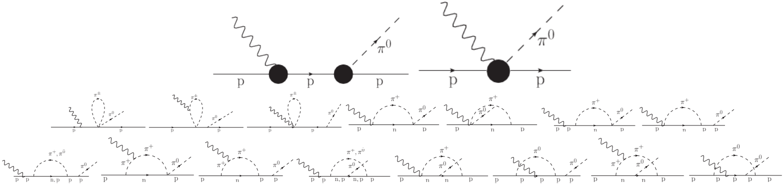
Inclusion of the Δ(1232)



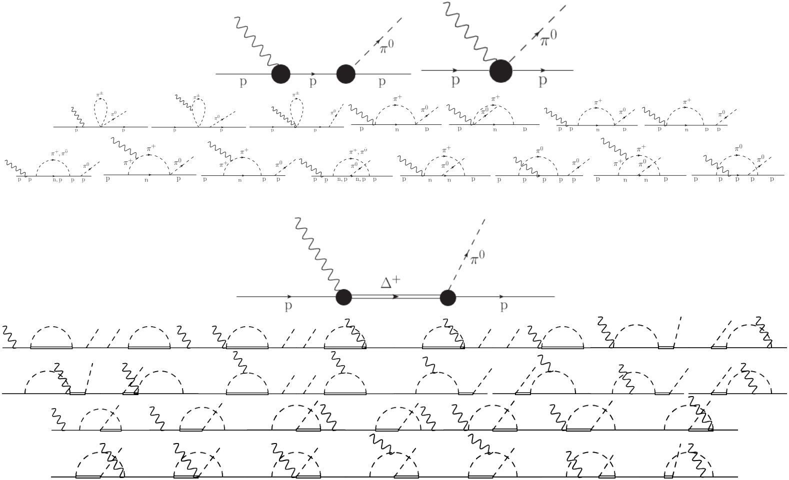
Geng et al., Phys. Lett. B 676 (2009) 63

$$\mathcal{L}_\Delta^{(1,2,3)} = \bar{\Psi}\left\{\frac{\mathrm{i} h_A}{2FM_\Delta} T^a \gamma^{\mu\nu\lambda}(\mathrm{D}_\lambda^{ab}\pi^a) + \frac{3e}{2m(m+M_\Delta)} T^3 \left(\mathrm{i} g_M \tilde{F}^{\mu\nu} - g_E \gamma_5 F^{\mu\nu}\right) + \text{H.c.}\right\}\partial_\mu \Delta_\nu + \cdots$$

All together: $\mathcal{O}(p^3)\ldots$

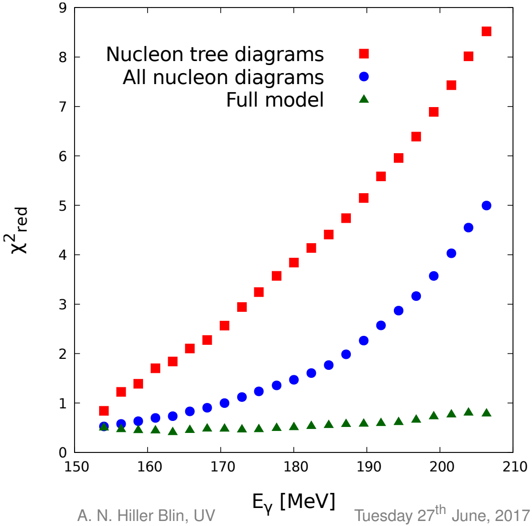


All together: $\mathcal{O}(p^3)$ and $\Delta(1232)$



First message

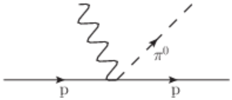
What could not be achieved without the $\Delta(1232)$ is now possible, **without the many new fitting constants of $\mathcal{O}(p^4)$**



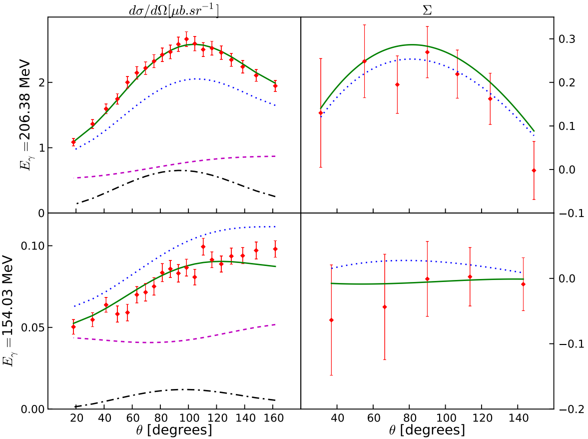
Fit of the low-energy constants

g_0	$\tilde{c}_{67}$	$\tilde{d}_{89} \cdot m_N^2$	$\tilde{d}_{168} \cdot m_N^2$	h_A	g_M	g_E	χ^2/d.o.f.
1.05	**2.29**	1.17	-10.4	**2.85**	**2.90**	3.53	0.96

- g_0, $\tilde{c}_{67} = c_6 + c_7$ **converge to the literature values**
  Ledwig et al. (2014) PRD
- g_M, h_A prefer low values, but **literature value** gives good fit
- $\tilde{d}_{89} = d_8 + d_9$, g_E are of natural size
- d_{18} is sensitive to higher-order input.
  We fit the combination $\tilde{d}_{168} = 2d_{16} - d_{18}$

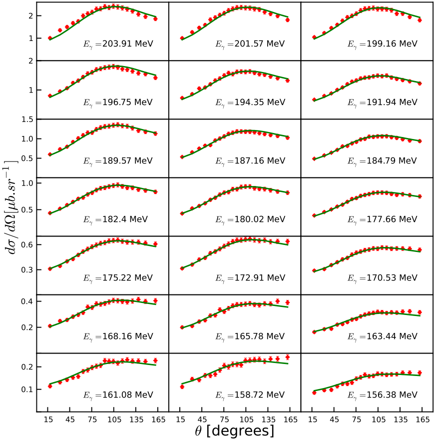


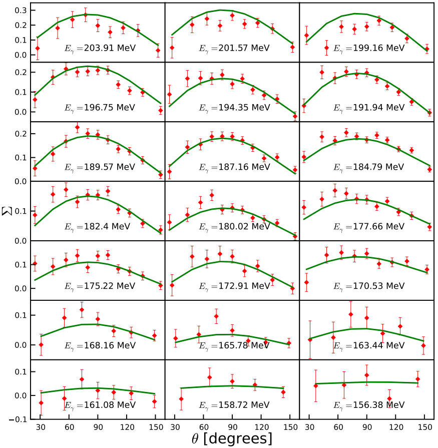
Comparing theoretical curves with data



- MAMI $\gamma p \to p\pi^0$ data
  Hornidge et al., Phys. Rev. Lett. 111 (2013) 062004
- $\mathcal{O}(p^3)$ nucleonic model
  Unable to reproduce the energy dependence
- $\mathcal{O}(p^{7/2})$ with $\Delta(1232)$
  Good reproduction for all 800 data points
- Only $\Delta(1232)$ contribution
- Only nucleonic contribution

All data points for $\mathrm{d}\sigma/\mathrm{d}\Omega$ and Σ





$\sim$ 800 data points

Summary

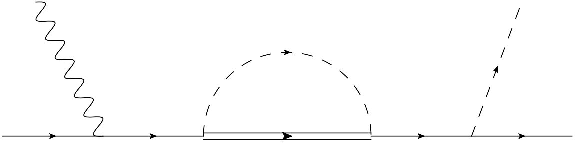
- High-quality description of $\gamma p \to p\pi^0$ threshold data
- **Cross sections** and **photon asymmetries** match experimental data at $E_\gamma > 170$ MeV **for the first time**
- $\mathcal{O}(p^3)$ with $\Delta(1232)$ better than $\mathcal{O}(p^4)$ without
- Strong constraints on previously unknown LECs

Outlook

- **Pion photoproduction**
  Cusp effect, charge production, photon virtuality, ...
- **Weak pion production**
  Work in progress (ANHB, Vicente Vacas, Yao)

Additional material

Matching a diagram to a specific order



$$O = 4L + \sum kV_k - 2\,\mathbf{N_\pi} - \mathbf{N_N} - N_\Delta \cdot \frac{1}{2}$$

- Propagators: pion $\sim \mathbf{m_\pi^{-2}}$, nucleon $\sim \mathbf{p_{ext}^{-1}}$
- $\Delta(1232)$: new scale $\delta = M_\Delta - m_N \approx 0.3$ GeV $> m_\pi$
- $\left(\frac{\delta}{m_N}\right)^2 \approx \left(\frac{m_\pi}{m_N}\right) \Longrightarrow$ far from resonance mass: $\sim m_\pi^{-1/2}$

Pascalutsa and Phillips, Phys. Rev. C 67 (2003) 055202

Renormalization

- Loop diagrams:
  divergences and **power counting breaking terms**

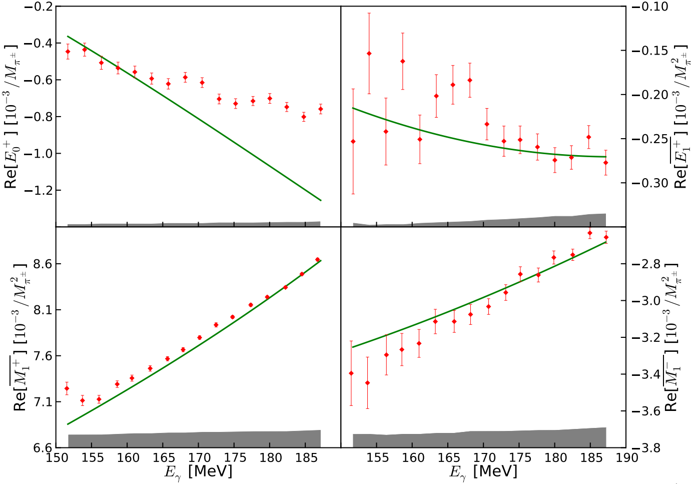
$$\frac{1}{\epsilon} = \frac{1}{4 - \text{dim}} \qquad \text{and} \qquad \text{e.g. terms } \propto p^2 \text{ at } \mathcal{O}(p^3)$$

- Fully analytical $\Longrightarrow$ match with **Lagrangian terms**
- **Low-energy constants** of these terms a priori unknwon
- EOMS-renormalization prescription:

  Gegelia and Japaridze, Phys. Rev. D 60 (1999) 114038

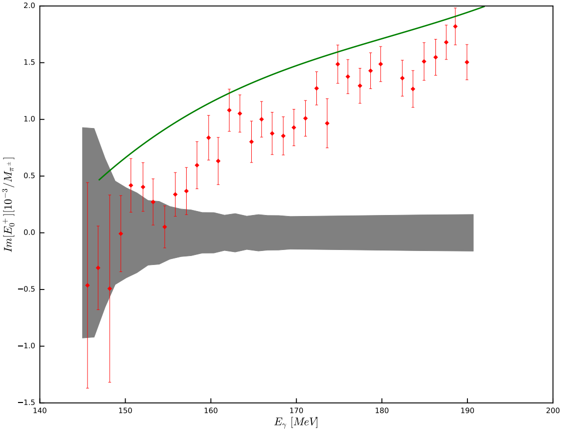
  - $\overline{MS}$ absorbs $L = \frac{2}{\epsilon} + \log(4\pi) - \gamma_E$ into LECs
  - Also subtracts PCBT by redefinition of LECs
  - Usually converges faster than other counting schemes (relativistic or not)

Multipoles — the real part



The explicit inclusion of Δ is essential to reproduce M_1^+

E_0^+ — the imaginary part



The contribution of *D*-waves needs to be taken into account in order to get the correct behavior for E_0^+

Schumann et al. (2015) PLB