Pion photo- and electroproduction and the chiral MAID interface [1]

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[1] Phys. Rev. C **87**, 045204 (2013), Phys. Rev. C **88**, 055207 (2013)

1. **Introduction**

2. **Renormalization and power counting**

3. **Application to pion photo- and electroproduction**

4. **Summary and outlook**

1. Introduction

Effective field theory

> ... if one writes down the most general possible Lagrangian, including all terms consistent with assumed symmetry principles, and then calculates matrix elements with this Lagrangian to any given order of perturbation theory, the result will simply be the most general possible S−matrix consistent with analyticity, perturbative unitarity, cluster decomposition and the assumed symmetry principles. ... [2]

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[2] S. Weinberg, Physica A **96**, 327 (1979)

... if we include in the Lagrangian all of the infinite number of interactions allowed by symmetries, then there will be a counterterm available to cancel every ultraviolet divergence. ... [3]

[3] S. Weinberg, *The Quantum Theory of Fields*, Vol. I, 1995, Chap. 12

Perturbative calculations in effective field theory require two main ingredients

1. Knowledge of the most general effective Lagrangian

   (a) Mesonic ChPT [SU(3)×SU(3)] [4] (π, K, η)

$$\underbrace{2}_{\mathcal{O}(q^2)} + \underbrace{10+2}_{\mathcal{O}(q^4)} + \underbrace{90+4+23}_{\mathcal{O}(q^6)} + \cdots$$

   - q: Small quantity such as a pion mass
   - Even powers
   - Two-loop level

[4] Gasser, Leutwyler (1985), Fearing, Scherer (1996), Bijnens, Colangelo, Ecker (1999), Ebertshäuser, Fearing, Scherer (2002) Bijnens, Girlanda, Talavera (2002)

(b) **Baryonic ChPT [SU(2)×SU(2)×U(1)]** [5] (π, N)

$$\underbrace{2}_{\mathcal{O}(q)} + \underbrace{7}_{\mathcal{O}(q^2)} + \underbrace{23}_{\mathcal{O}(q^3)} + \underbrace{118}_{\mathcal{O}(q^4)} + \quad \ldots$$

- **Odd and even powers (spin)**
- **One-loop level**

Each term comes with an independent low-energy constant (LEC)

Lowest-order Lagrangians: F, $M^2 = 2B\hat{m}$, m, g_A
Higher-order Lagrangians: l_i, c_i, d_i, e_i, ...

[5] Gasser, Sainio, Švarc (1988), Bernard, Kaiser, Meißner (1995), Ecker, Mojžiš (1996), Fettes, Meißner, Mojžiš, Steininger (2000)

2. Consistent expansion scheme for observables

(a) Tree-level diagrams, loop diagrams $\rightsquigarrow$ ultraviolet divergences, regularization (of infinities)

(b) Renormalization condition

(c) Power counting scheme for renormalized diagrams

(d) Remove regularization

ChPT: Momentum and quark mass expansion at fixed ratio m_{quark}/q^2 [6]

[6] J. Gasser and H. Leutwyler, Annals Phys. **158**, 142 (1984)

2. Renormalization and power counting

- **Most general Lagrangian**

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\pi} + \mathcal{L}_{\pi N} = \mathcal{L}_{\pi}^{(2)} + \mathcal{L}_{\pi}^{(4)} + \ldots + \mathcal{L}_{\pi N}^{(1)} + \mathcal{L}_{\pi N}^{(2)} + \ldots$$

Basic Lagrangian

$$\mathcal{L}_{\pi N}^{(1)} = \bar{\Psi}\left(i\gamma_\mu\partial^\mu - \boxed{m}\right)\Psi - \frac{1}{2}\frac{\boxed{\mathrm{g}_A}}{F}\bar{\Psi}\gamma_\mu\gamma_5\tau^a\partial^\mu\pi^a\Psi + \cdots$$

m, g_A, and F denote the chiral limit of the physical nucleon mass, the axial-vector coupling constant, and the pion-decay constant, respectively

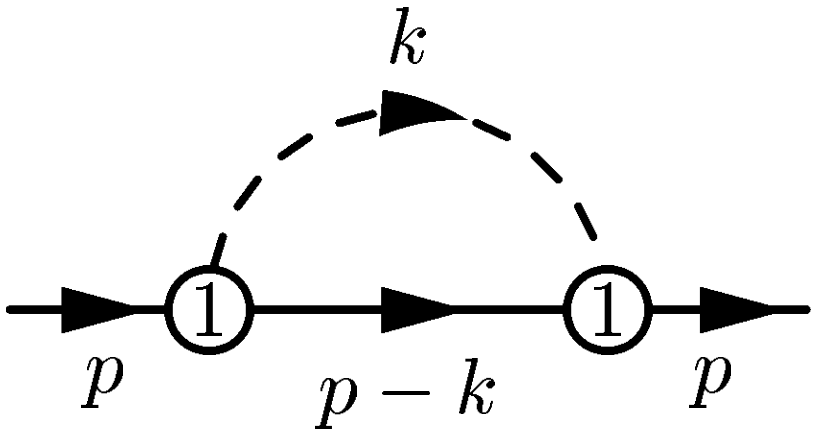
- Power counting: Associate chiral order D with a diagram
  - Square of the lowest-order pion mass:
    $M^2 = B(m_u + m_d) \sim \mathcal{O}(q^2)$
  - Nucleon mass in the chiral limit $m \sim \mathcal{O}(q^0)$
  - Loop integration in n dimensions $\sim \mathcal{O}(q^n)$
  - Vertex from $\mathcal{L}_\pi^{(2k)} \sim \mathcal{O}(q^{2k})$
  - Vertex from $\mathcal{L}_{\pi N}^{(k)} \sim \mathcal{O}(q^k)$
  - Nucleon propagator $\sim \mathcal{O}(q^{-1})$
  - Pion propagator $\sim \mathcal{O}(q^{-2})$

- Renormalization
  - Regularize (typically dimensional regularization)

$$
\begin{aligned}
I(M^2,\mu^2,n) &= \mu^{4-n}\int \frac{d^nk}{(2\pi)^n}\frac{i}{k^2-M^2+i0^+} \\
&= \frac{M^2}{16\pi^2}\left[R+\ln\left(\frac{M^2}{\mu^2}\right)\right]+O(n-4), \\
\boxed{\mathsf{R}} &= \frac{2}{n-4}-[\mathsf{ln}(4\pi)+\Gamma'(1)]-1 \rightarrow \boxed{\infty}
\end{aligned}
$$

  - Adjust counterterms such that they absorb all the divergences occurring in the calculation of loop diagrams
  - Renormalization prescription: Adjust finite pieces such that renormalized diagrams satisfy a given power counting

- **Example: Contribution to nucleon mass**



Goal: $D = n \cdot 1 - 2 \cdot 1 - 1 \cdot 1 + 2 \cdot 1 = n - 1$

$$\Sigma = -\frac{3g_{A0}^2}{4F_0^2}\left[(\not{p}+m)I_N + M^2(\not{p}+m)I_{N\pi}(-p,0) + \cdots\right]$$

Apply $\widetilde{\mathrm{MS}}$ renormalization scheme

$$\Sigma_r = -\frac{3g_{Ar}^2}{4F_r^2}[M^2(\not{p}+m)\underbrace{I_{N\pi}^r(-p,0)}_{=-\frac{1}{16\pi^2}+\ldots} + \ldots] = \boxed{\mathcal{O}(q^2)}$$

GSS [7]: It turns out that loops have a much more complicated low-energy structure if baryons are included. Because the nucleon mass m_N does not vanish in the chiral limit, the mass scale m (nucleon mass in the chiral limit) occurs in the effective Lagrangian $\mathcal{L}_{\pi N}^{(1)}$ .... This complicates life a lot.

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[7] J. Gasser, M. E. Sainio, A. Švarc, Nucl. Phys. **B307**, 779 (1988)

One possible solution: Extended on-mass-shell (EOMS) scheme[8]

Main idea: Perform additional subtractions such that renormalized diagrams satisfy the power counting

Motivation for this approach[9]

Terms violating the power counting are analytic in small quantities (and can thus be absorbed in a renormalization of counterterms)

- Example (chiral limit)

$$H(p^2, m^2; n) = -\int \frac{d^n k}{(2\pi)^n} \frac{i}{[(k-p)^2 - m^2 + i0^+][k^2 + i0^+]}$$

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[8] T. Fuchs, J. Gegelia, G. Japaridze, S. Scherer, Phys. Rev. D **68**, 056005 (2003)

[9] J. Gegelia and G. Japaridze, Phys. Rev. D **60**, 114038 (1999)

Small quantity

$$\Delta = \frac{p^2 - m^2}{m^2} = \mathcal{O}(q)$$

We want the renormalized integral to be of order

$$D = n - 1 - 2 = n - 3$$

Result of integration

$$H \sim F(n, \Delta) + \Delta^{n-3} G(n, \Delta)$$

- F and G are hypergeometric functions
- analytic in Δ for arbitrary n

Observation[10]

F corresponds to first expanding the integrand in small quantities and then performing the integration

$\Rightarrow$ Algorithm: Expand integrand in small quantities and subtract those (integrated) terms whose order is smaller than suggested by the power counting

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[10] J. Gegelia, G. Japaridze, K. S. Turashvili, Theor. Math. Phys. **101**, 1313 (1994)

Here:

$$H^{\mathrm{subtr}} = -\int \frac{d^n k}{(2\pi)^n} \frac{i}{(k^2 - 2k\cdot p + i0^+)(k^2 + i0^+)}\bigg|_{p^2=m^2}$$

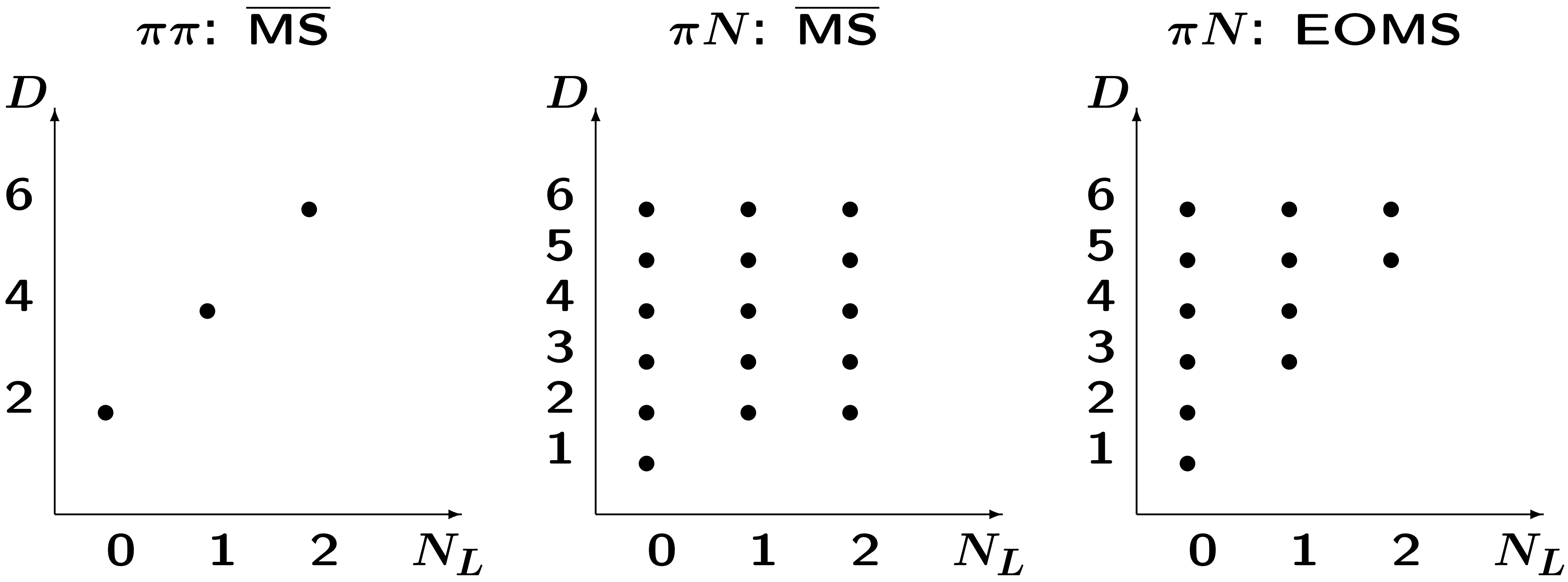
$$= -2\bar{\lambda} + \frac{1}{16\pi^2} + O(n-4)$$

where

$$\bar{\lambda} = \frac{m^{n-4}}{(4\pi)^2}\left\{\frac{1}{n-4} - \frac{1}{2}\left[\ln(4\pi) + \Gamma'(1) + 1\right]\right\}$$

$$H^R = H - H^{\mathrm{subtr}} = \mathcal{O}(q^{n-3})$$

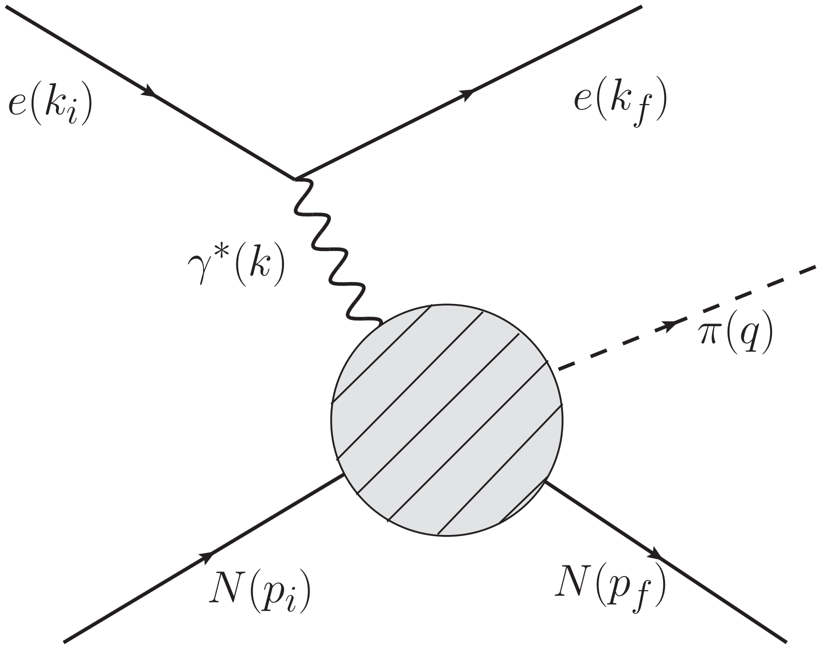
Chiral versus loop expansion



3. Application to pion photo- and electroproduction

$$e(k_i) + N(p_i) \to e(k_f) + N(p_f) + \pi(q)$$

One-photon-exchange approximation



Invariant amplitude

$$\mathcal{M} = \text{leptonic vertex} \times i\,\text{propagator} \times \text{hadronic vertex} = \epsilon_\mu \mathcal{M}^\mu$$

$$\epsilon_\mu = e\frac{\bar{u}(k_f)\gamma_\mu u(k_i)}{k^2}, \qquad \mathcal{M}^\mu = -ie\langle N(p_f), \pi(q)|J^\mu(0)|N(p_i)\rangle.$$

Current conservation

$$k_\mu \mathcal{M}^\mu = 0$$

Parameterization in terms of six invariant amplitudes

$$\mathcal{M}^\mu = \bar{u}(p_f)\left(\sum_{i=1}^{6} \boxed{A_i(s,t,u)} M_i^\mu\right)u(p_i), \qquad u(p)\text{: Dirac spinor}$$

Mandelstam variables

$$s + t + u = 2m_N^2 + M_\pi^2 - Q^2, \qquad Q^2 = -k^2$$

$$M_1^\mu = -\frac{i}{2}\gamma_5\left(\gamma^\mu \not{k} - \not{k}\gamma^\mu\right), \qquad \ldots$$

cm frame

$$\mathcal{M} = \frac{4\pi W}{m_N}\chi_f^\dagger \mathcal{F}\chi_i, \quad \chi\text{: Pauli spinor}$$

six CGLN amplitudes

$$\mathcal{F} = i\vec{\sigma}\cdot\vec{a}_\perp \boxed{\mathcal{F}_1(W,\Theta_\pi,Q^2)} + \ldots$$

Multipole expansion of $\mathcal{F}_i$ in terms of Legendre polynomials and

$$\mathcal{F}_1 = \sum_{l=0}^{\infty}\left\{[lM_{l+} + E_{l+}]P'_{l+1}(x) + [(l+1)M_{l-} + E_{l-}]P'_{l-1}(x)\right\}, \quad \ldots$$

$$x = \cos\Theta_\pi = \hat{q}\cdot\hat{k}$$

$E_{l\pm}, M_{l\pm}, L_{l\pm}$: functions of W and Q^2

Isospin decomposition: **four physical channels**

$$\begin{aligned} A_i(\gamma^{(*)}p \to n\pi^+) &= \sqrt{2}\left(A_i^{(-)} + A_i^{(0)}\right), \\ A_i(\gamma^{(*)}p \to p\pi^0) &= A_i^{(+)} + A_i^{(0)}, \\ A_i(\gamma^{(*)}n \to p\pi^-) &= -\sqrt{2}\left(A_i^{(-)} - A_i^{(0)}\right), \\ A_i(\gamma^{(*)}n \to n\pi^0) &= A_i^{(+)} - A_i^{(0)}, \end{aligned}$$

expressed in terms of **three isospin amplitudes** **(0), (+), and (−)**

1. Number of diagrams

   - $\mathcal{O}(q^3)$: 15 tree-level diagrams + 50 one-loop diagrams
   - $\mathcal{O}(q^4)$: 20 tree-level diagrams + 85 one-loop diagrams

2. Calculate loop contributions numerically using CAS MATHEMATICA with FeynCalc and LoopTools packages

3. Checks: Current conservation and crossing symmetry

4. LECs from other processes (mesonic and baryonic Lagrangians)

LEC	Source
l_3	$M_\pi = 134.977$ MeV
l_4, l_6	pion form factor
c_1	proton mass $m_p = 938.272$ MeV
c_2, c_3, c_4	pion-nucleon scattering
c_6, c_7	magnetic moment of proton ($\mu_p = 2.793$) and neutron ($\mu_n = -1.913$)
d_6, d_7, e_{54}, e_{74}	world data for nucleon electromagnetic form factors ($Q^2 < 0.3$ GeV^2)
d_{16}	axial-vector coupling constant $g_A = 1.2695$
d_{18}	pion-nucleon coupling
d_{22}	axial radius of the nucleon $\langle r_A^2 \rangle = 12/M_A^2$, $M_A = 1.026$ GeV

l_i: $\mathcal{L}_\pi^{(4)}$,

c_i: $\mathcal{L}_{\pi N}^{(2)}$, d_i: $\mathcal{L}_{\pi N}^{(3)}$, e_i: $\mathcal{L}_{\pi N}^{(4)}$

5. Analytic expressions for the contact diagrams

(a) 4 LECs at $\mathcal{O}(q^3)$

isospin

$$\mathcal{L}_{\pi N}^{(3)} = \frac{d_8}{2m}\left(i\bar{\Psi}\epsilon^{\mu\nu\alpha\beta}\mathrm{Tr}\left(\tilde{f}_{\mu\nu}^{+}u_\alpha\right)D_\beta\Psi + \text{H.c.}\right) \qquad (+)$$

$$+\frac{d_9}{2m}\left(i\bar{\Psi}\epsilon^{\mu\nu\alpha\beta}\mathrm{Tr}\left(f_{\mu\nu}^{+} + 2v_{\mu\nu}^{(s)}\right)u_\alpha D_\beta\Psi + \text{H.c.}\right) \qquad (0)$$

$$-\frac{d_{20}}{8m^2}\left(i\bar{\Psi}\gamma^\mu\gamma_5\left[\tilde{f}_{\mu\nu}^{+}, u_\lambda\right]D^{\lambda\nu}\Psi + \text{H.c.}\right) \qquad (-)$$

$$+i\frac{d_{21}}{2}\bar{\Psi}\gamma^\mu\gamma_5\left[\tilde{f}_{\mu\nu}^{+}, u^\nu\right]\Psi \qquad (-)$$

Structures contribute to photoproduction, no free parameters for electroproduction

(b) 15 LECs at $\mathcal{O}(q^4)$

$$\mathcal{L}_{\pi N}^{(4)} = -\frac{e_{48}}{4m}\left(i\bar{\Psi}\mathrm{Tr}\left(f_{\lambda\mu}^{+} + 2v_{\lambda\mu}^{(s)}\right) h_{\nu}^{\lambda}\gamma_5\gamma^{\mu}D^{\nu}\Psi + \text{H.c.}\right)$$
$$+ \text{14 more terms}$$

- photoproduction

isospin channel	(0)	(+)	(−)
# LECs	5	5	1

- electroproduction

isospin channel	(0)	(+)	(−)
# LECs	2	2	0

6. Web interface chiral MAID

[http://www.kph.uni-mainz.de/MAID/chiralmaid/]

M A I D

Photo- and Electroproduction of Pions, Etas and Kaons on the Nucleon

Institut für Kernphysik, Universität Mainz

Mainz, Germany

MAID2007	unitary isobar model for (e,e'p)
DMT2001	dynamical model for (e,e'p)
KAON-MAID	isobar model for (e,e'K)
ETA-MAID	isobar model for (e,e'h) reggeized isobar model for (g,h)
ChiralMAID NEW	chiral perturbation theory approach for (e,e'p)
2-PION-MAID	isobar model for (g,pp)
archive	MAID2000 MAID2003 DMT2001original ETAprime2003

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MAID

ChiralMAID info and updates (please read first)

Pion Photo- and Electroproduction on the Nucleon in relativistic chiral perturbation theory

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- Electromagnetic Multipoles ($E_{l\pm}$, $M_{l\pm}$, $L_{l\pm}$, $S_{l\pm}$)
- Amplitudes (F_1,...,F_6, H_1,...,H_6, A_1,...,A_6)
- Differential Cross Sections (ds_T, ds_L, ds_{LT}, ds_{TT}, ...)
- 5-fold Diff. Cross Section (d^5s, G, ds^V= ds_T+e ds_L+e ds_{TT} cos 2f + ...)
- Total Cross Sections (s_T , s_L , $s_{LT'}$, $s_{TT'}$, ...)
- Transverse Polarization Observables (ds/dW, T, S, P, E, F, G, H, ...)

External services:
MAID Homepage MAID2003 DMT2001 KAON-MAID ETA-MAID2000 ETA-MAID2003 ETA'-MAID

A1 kinematics calculator for electroproduction (Java)
SAID Partial-Wave Analyses

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Multipoles

The multipoles can be given in 4 unique sets of isospin or charge channels (click here for a larger image):

$$\left(A_p^{1/2}, A_n^{1/2}, A^{3/2}\right), \left(A^{1/2}, A^0, A^{3/2}\right), \left(A^0, A^+, A^-\right), \left(A_{\pi^+n}, A_{\pi^-p}, A_{\pi^0p}, A_{\pi^0n}\right)$$

$$A_{\pi^+n} = \sqrt{2}\left(A^- + A^0\right) = \sqrt{2}\left(A_p^{1/2} - \tfrac{1}{3}A^{3/2}\right) = \sqrt{2}\left(A^0 + \tfrac{1}{3}A^{1/2} - \tfrac{1}{3}A^{3/2}\right)$$

$$A_{\pi^-p} = -\sqrt{2}\left(A^- - A^0\right) = \sqrt{2}\left(A_n^{1/2} + \tfrac{1}{3}A^{3/2}\right) = \sqrt{2}\left(A^0 - \tfrac{1}{3}A^{1/2} + \tfrac{1}{3}A^{3/2}\right)$$

$$A_{\pi^0p} = A^+ + A^0 = A_p^{1/2} + \tfrac{2}{3}A^{3/2} = A^0 + \tfrac{1}{3}A^{1/2} + \tfrac{2}{3}A^{3/2}$$

$$A_{\pi^0n} = A^+ - A^0 = -A_n^{1/2} + \tfrac{2}{3}A^{3/2} = -A^0 + \tfrac{1}{3}A^{1/2} + \tfrac{2}{3}A^{3/2}$$

Further details can be found in D. Drechsel and L. Tiator, J. Phys. G 18 (1992) 449-497. (scanned version)

Type of the multipoles: ○ (p(1/2), n(1/2), 3/2) ○ (1/2, 0, 3/2) ○ (0, +, -) ◉ charge channels

Choose pion angular momentum l : [0] ☑ El+ ☐ El- ☐ Ml+ ☐ Ml- ☐ Ll+ ☐ Ll- ☐ Sl+ ☐ Sl-

Reduced multipoles: ☐

Choose kinematical variables

choose an independent (running) variable: ○ Q^2 ◉ W

choose values for Q^2, W, step size and maximum value:

Q^2 $(GeV/c)^2$	W (MeV)	increment	upper value	click here	
0	1074	1	1100	Calculate	Reset

Change of model parameters:

$O(q^3)$ (all couplings in GeV^{-2})

0		+		-	
d_9		d_8		d_{20}	d_{21}
-1.216		-1.092		4.337	-4.260

$O(q^4)$ (all couplings in GeV^{-3})

Isospin 0

e_{48}	e_{49}	e_{50}	e_{51}	e_{52}	e_{53}	e_{112}
5.235	0.925	2.205	6.629	-4.103	-2.654	9.342

Isospin +

e_{67}	e_{68}	e_{69}	e_{71}	e_{72}	e_{73}	e_{113}
-8.269	-0.925	-1.035	-4.352	10.539	2.120	-13.745

Isospin -

e_{70}
3.910

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Multipoles

```
                C h M A I D  2 0 1 2
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       *************************************************

  Pion angular momentum l= 0

  All multipoles are given in 10^-3/Mpi+

                 Q^2 =    .000 (GeV/c)^2
                 ***********************
  .3028  1.2695   .0924 13.2100                                       e,gA,F[GeV],gpiN=gA*mp/F
-1.0920 -1.2160  4.3370 -4.2600                                       d8,d9,d20,d21 [GeV^-2]
 5.2350   .9250  2.2050  6.6290 -4.1030 -2.6540                       e48,e49,e50,e51,e52,e53 [GeV^-3]
-8.2690  -.9250 -1.0350  3.9100 -4.3520 10.5390  2.1200               e67,e68,e69,e70,e71,e72,e73 [GeV^-3]
 9.3420-13.7450                                                       e112,e113 [GeV^-3]
```

W	E0+(pi0_p)		E0+(pi0_n)		E0+(pi+_n)		E0+(pi-_p)		E(lab)	q(cm)
(MeV)	Re	Im	Re	Im	Re	Im	Re	Im	(MeV)	(MeV)
1074.00	-1.0608	.0000	2.8400	.0000	27.1931	.0000	-32.7097	.0000	145.54	13.44
1075.00	-.9960	.0000	2.8898	.0000	26.9933	.0000	-32.4886	.0000	146.69	20.45
1076.00	-.9210	.0000	2.9504	.0000	26.7940	.0000	-32.2689	.0000	147.84	25.64
1077.00	-.8301	.0000	3.0279	.0000	26.5939	.0000	-32.0500	.0000	148.98	29.96
1078.00	-.7093	.0000	3.1376	.0000	26.3903	.0000	-31.8308	.0000	150.13	33.75
1079.00	-.4769	.0000	3.3685	.0000	26.1676	.0000	-31.6058	.0000	151.28	37.18
1080.00	-.3758	.3249	3.4564	.3534	25.9705	-.0617	-31.3900	.0215	152.43	40.33
1081.00	-.3959	.4764	3.4121	.5183	25.7986	-.0924	-31.1839	.0331	153.58	43.27
1082.00	-.4162	.5891	3.3672	.6412	25.6292	-.1166	-30.9798	.0430	154.74	46.03
1083.00	-.4367	.6826	3.3218	.7433	25.4625	-.1378	-30.7777	.0521	155.89	48.66
1084.00	-.4573	.7641	3.2758	.8323	25.2982	-.1573	-30.5776	.0609	157.04	51.16
1085.00	-.4780	.8371	3.2293	.9121	25.1364	-.1757	-30.3793	.0696	158.20	53.55
1086.00	-.4989	.9035	3.1822	.9849	24.9770	-.1933	-30.1829	.0782	159.36	55.86
1087.00	-.5199	.9649	3.1346	1.0523	24.8200	-.2104	-29.9883	.0868	160.52	58.08
1088.00	-.5410	1.0221	3.0864	1.1151	24.6654	-.2270	-29.7954	.0955	161.67	60.24
1089.00	-.5623	1.0758	3.0377	1.1741	24.5131	-.2433	-29.6042	.1043	162.83	62.33
1090.00	-.5837	1.1264	2.9884	1.2299	24.3630	-.2593	-29.4147	.1131	164.00	64.36
1091.00	-.6053	1.1745	2.9384	1.2828	24.2152	-.2752	-29.2268	.1220	165.16	66.34
1092.00	-.6271	1.2202	2.8880	1.3333	24.0695	-.2909	-29.0405	.1310	166.32	68.27

Fits to available experimental data

1. $\gamma + p \to p + \pi^0$

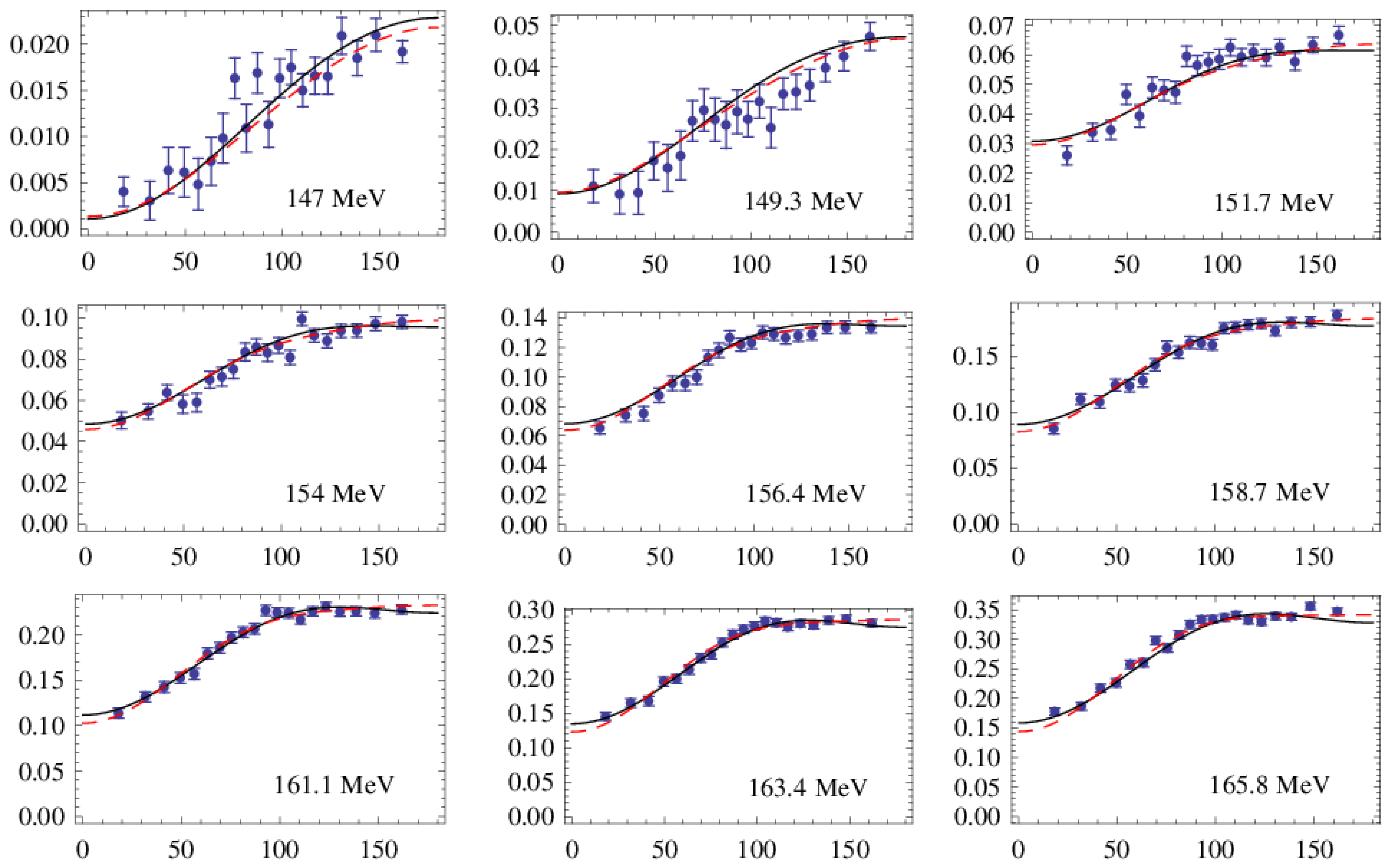
2. $\gamma^* + p \to p + \pi^0$

3. $\gamma + p \to n + \pi^+$ and $\gamma + n \to p + \pi^-$

4. $\gamma^{(*)} + p \to n + \pi^+$

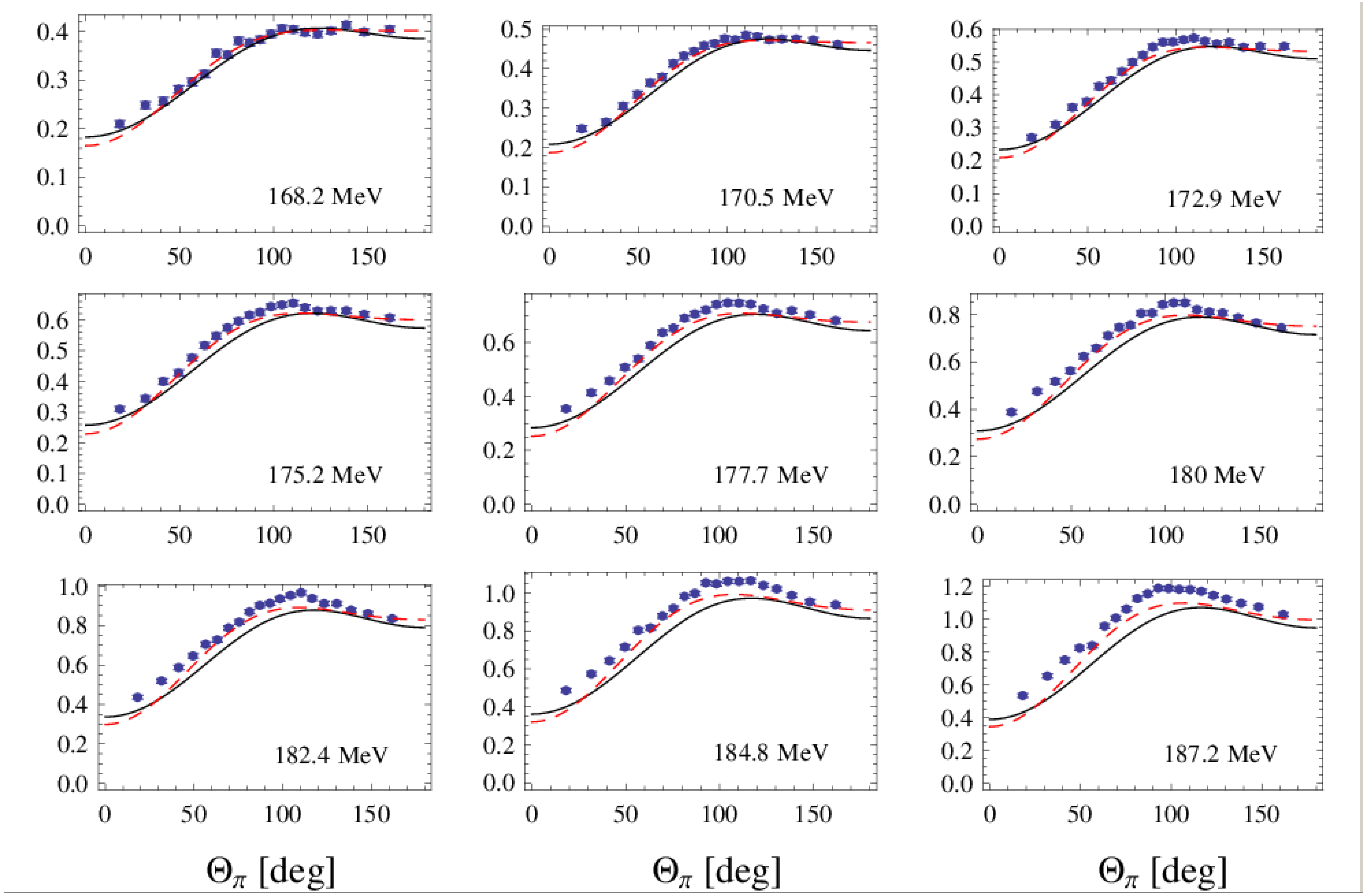
Differential cross sections $d\sigma/d\Omega_\pi$ in μb/sr for $\gamma + p \to p + \pi^0$ [11]

Solid: RChPT, dashed HBChPT



[11] Data taken from D. Hornidge et al., Phys. Rev. Lett. **111**, 062004 (2013)

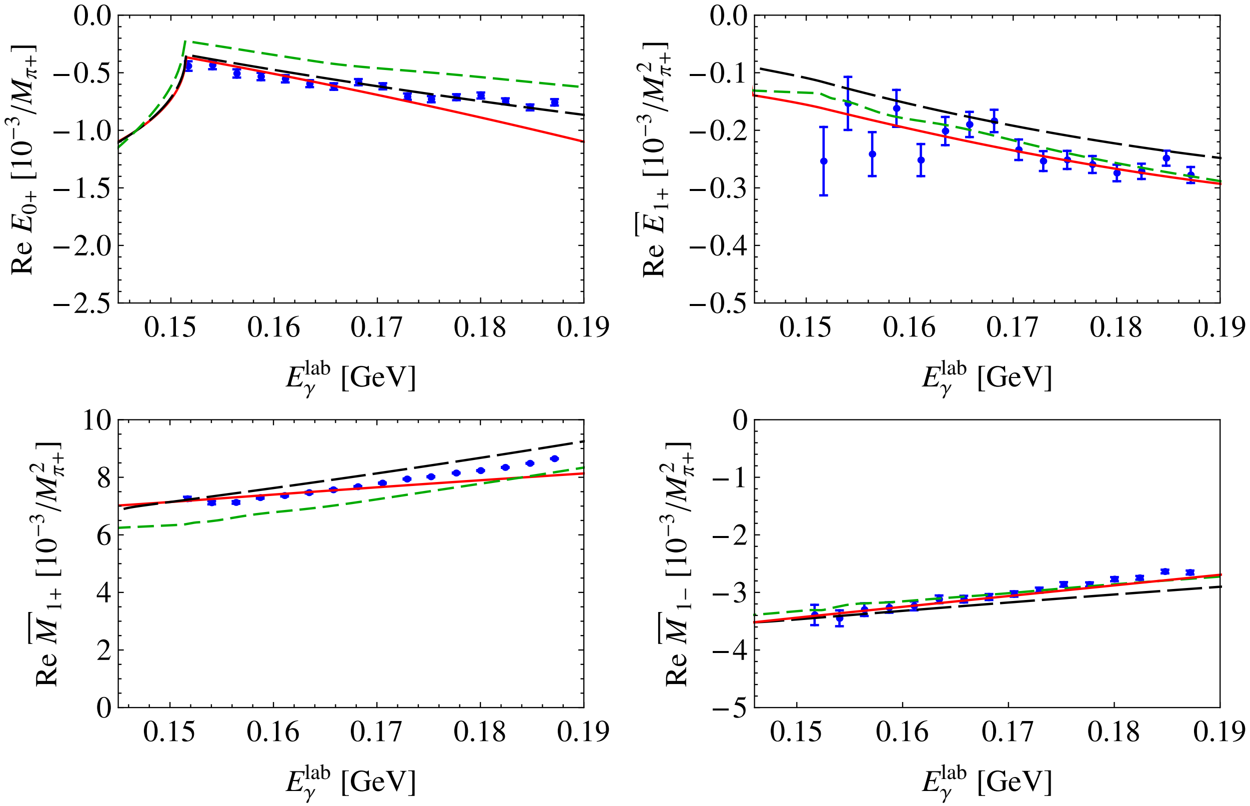
Differential cross sections $d\sigma/d\Omega_\pi$ in μb/sr for $\gamma + p \rightarrow p + \pi^0$ [12]



Solid: RChPT, dashed HBChPT

[12] Data taken from D. Hornidge et al., Phys. Rev. Lett. **111**, 062004 (2013)

S- and reduced P-wave multipoles for $\gamma + p \to p + \pi^0$



Red RChPT; green DMT model [13]; black Gasparyan & Lutz [14]; data from Hornidge et al. (2013)

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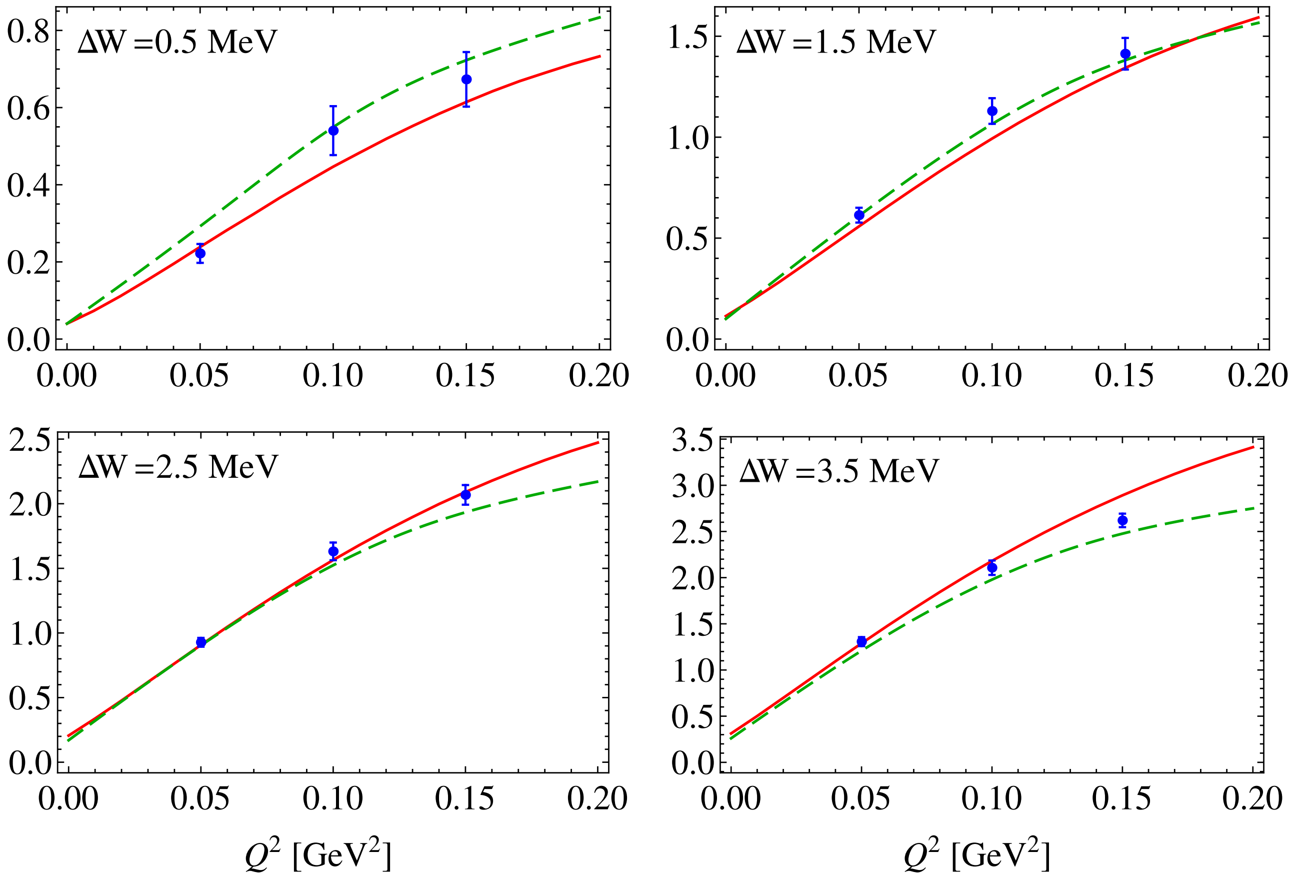
[13] S. S. Kamalov et al., Phys. Rev. C **64**, 032201 (2001)

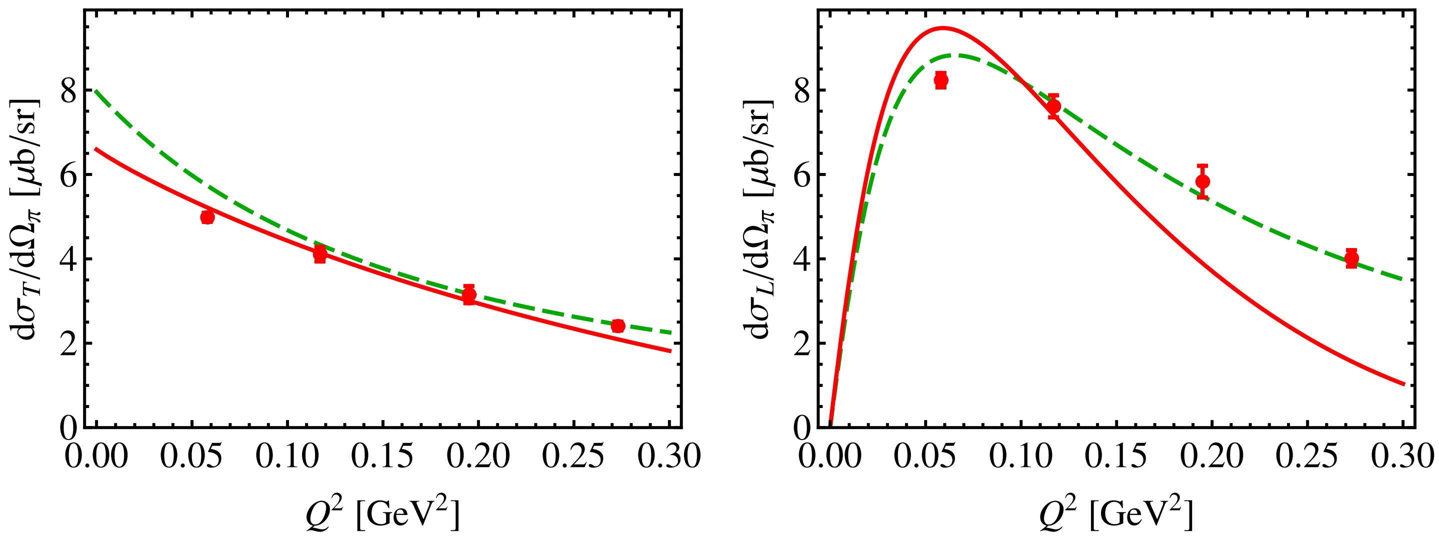
[14] A. Gasparyan and M. F. M. Lutz, Nucl. Phys. **A848**, 126 (2010)

Total cross sections for $\gamma^* + p \to p + \pi^0$ in μb



red RChPT;
green DMT model;
data from Merkel et al. 2009, 2011

Differential cross sections as a function of Q^2 for $\gamma^* + p \to n + \pi^+$ at $W = 1125$ MeV and $\Theta_\pi = 0°$.



red RChPT; green DMT model;
data from Baumann (PhD thesis, JGU, 2005)

from fits with all data

Isospin channel	LEC	Value
0	d_9 [GeV^{-2}]	-1.22 ± 0.12
0	e_{48} [GeV^{-3}]	5.2 ± 1.4
0	e_{49} [GeV^{-3}]	0.9 ± 2.6
0	e_{50} [GeV^{-3}]	2.2 ± 0.8
0	e_{51} [GeV^{-3}]	6.6 ± 3.6
0	e^*_{52} [GeV^{-3}]	-4.1
0	e^*_{53} [GeV^{-3}]	-2.7
0	e_{112} [GeV^{-3}]	9.3 ± 1.6
+	d_8 [GeV^{-2}]	-1.09 ± 0.12
+	e_{67} [GeV^{-3}]	-8.3 ± 1.5
+	e_{68} [GeV^{-3}]	-0.9 ± 2.6
+	e_{69} [GeV^{-3}]	-1.0 ± 2.2
+	e_{71} [GeV^{-3}]	-4.4 ± 3.7
+	e^*_{72} [GeV^{-3}]	10.5
+	e^*_{73} [GeV^{-3}]	2.1
+	e_{113} [GeV^{-3}]	-13.7 ± 2.6
−	d_{20} [GeV^{-2}]	4.34 ± 0.08
−	d_{21} [GeV^{-2}]	-3.1 ± 0.1
−	e_{70} [GeV^{-3}]	3.9 ± 0.3

4. Summary and outlook

- Baryonic ChPT: Renormalization condition $\leftrightarrow$ consistent power counting

- Example: EOMS renormalization (manifestly Lorentz-invariant)

- Application to pion photo- and electroproduction

- 20 tree-level diagrams + 85 one-loop diagrams

- Chiral MAID interface

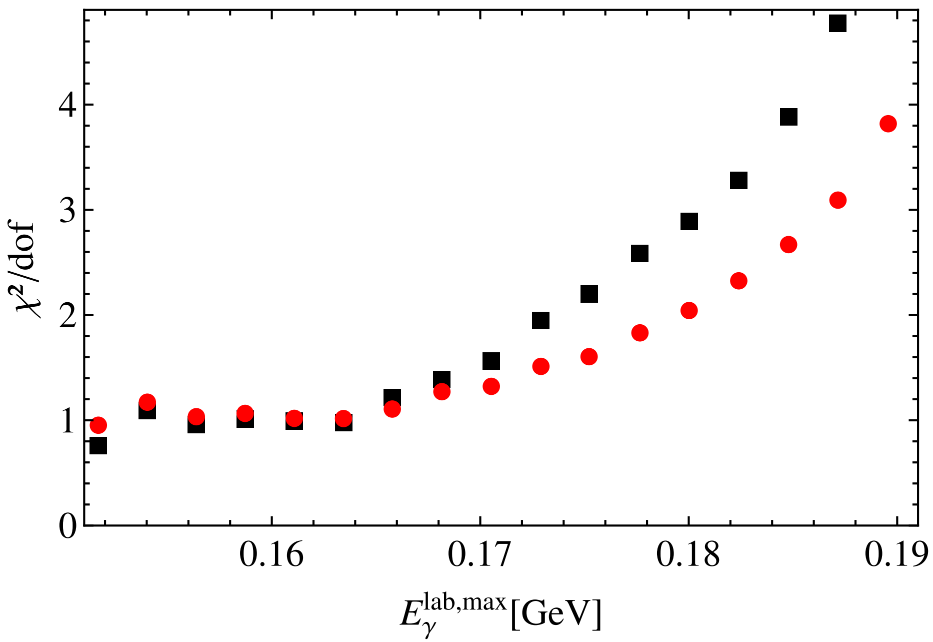
- **Inclusion of heavy degrees of freedom (vector mesons, axial vector mesons, Δ [15])**

- **New data [16] $\rightsquigarrow$ reanalysis of LECs**

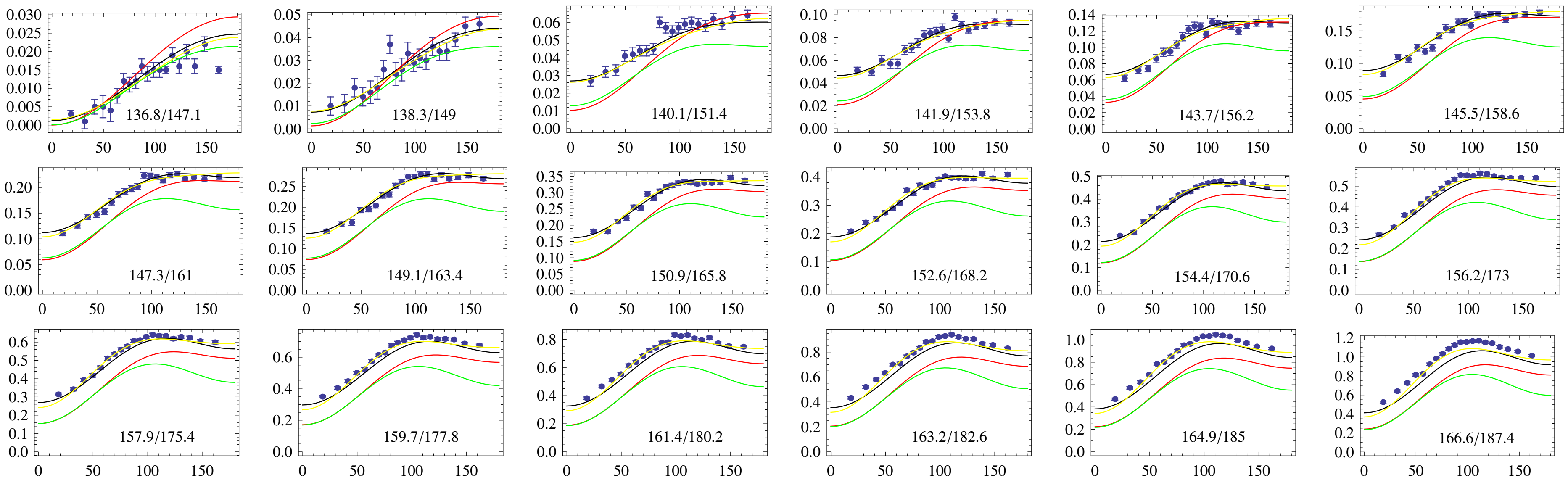
[15] A. N. H. Blin, T. Ledwig and M. J. V. Vacas, arXiv:1412.4083 [hep-ph]

[16] K. Chirapatpimol *et al.*, $p(e,e'p)\pi^0$, Phys. Rev. Lett. **114**, 192503 (2015), I. Fricic, $p(e,e'\pi^+)n$, PhD thesis, University of Zagreb, 2015

$\chi^2_{\mathbf{red}}$ **as a function of the fitted energy range: RBChPT vs. HBChPT**



Differential cross sections $d\sigma/d\Omega_\pi$ in μb/sr for $\gamma + p \to p + \pi^0$ [17]



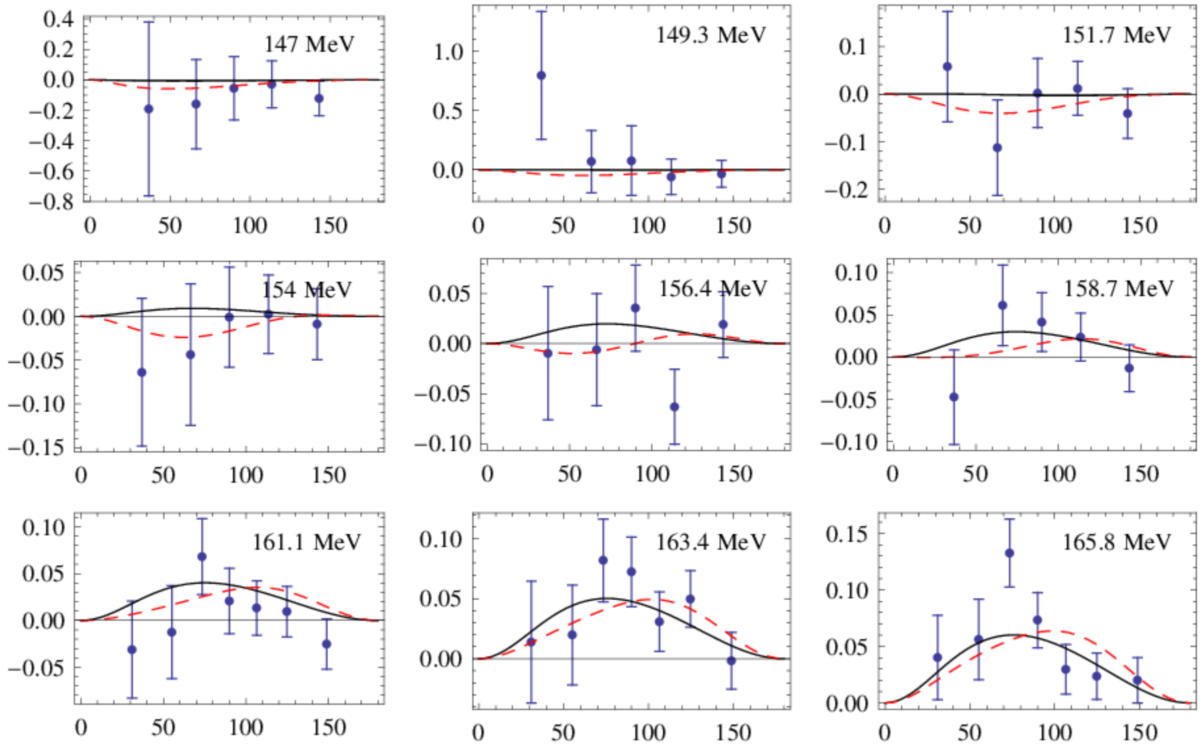
Black: RChPT $\mathcal{O}(q^4)$, red RChPT $\mathcal{O}(q^3)$, yellow HChPT $\mathcal{O}(q^4)$, green RChPT + vector mesons $\mathcal{O}(q^3)$

---

[17] Data taken from D. Hornidge et al., Phys. Rev. Lett. **111**, 062004 (2013)

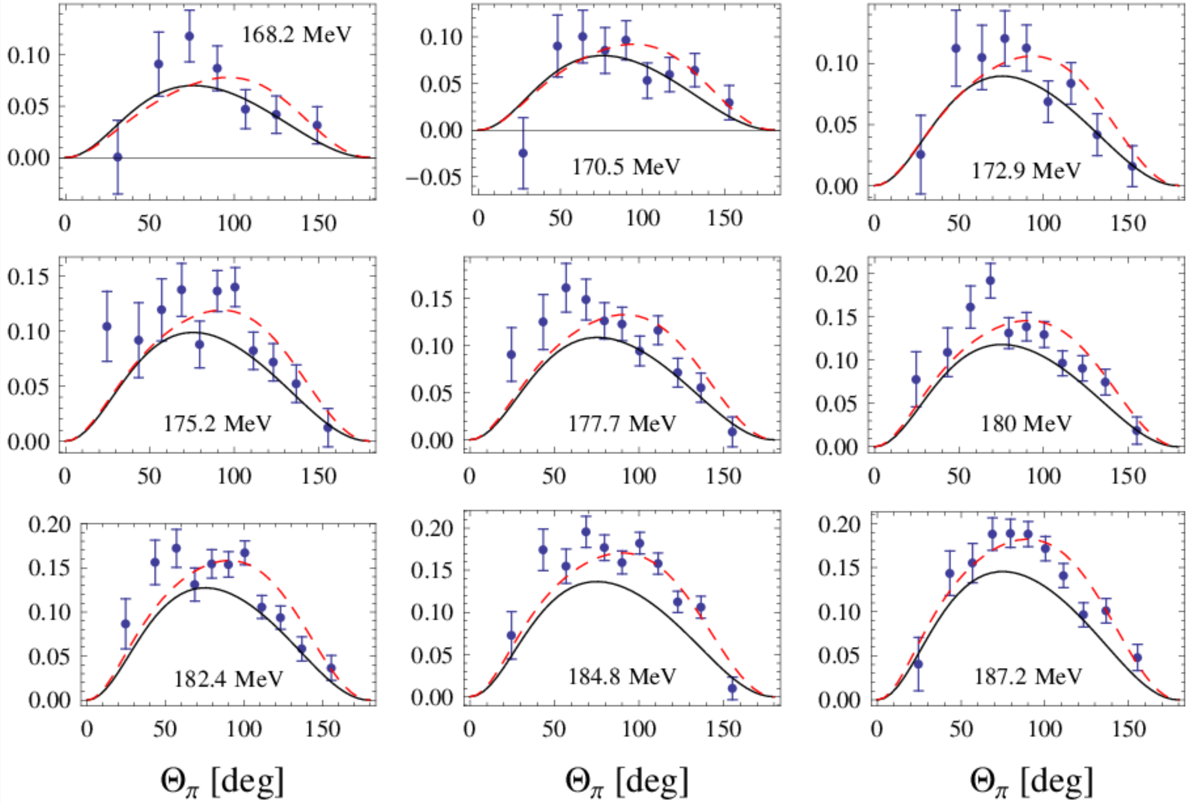
Photon asymmetries for $\gamma + p \to p + \pi^0$ [18]

Solid: RChPT, dashed HBChPT



[18] Data taken from D. Hornidge et al., Phys. Rev. Lett. **111**, 062004 (2013)

Photon asymmetries for $\gamma + p \to p + \pi^0$ [19]



Solid: RChPT, dashed HBChPT

[19] Data taken from D. Hornidge et al., Phys. Rev. Lett. **111**, 062004 (2013)

Multipoles

The multipoles can be given in 4 unique sets of isospin or charge channels (click here for a larger image):

$$\left(A_p^{1/2}, A_n^{1/2}, A^{3/2}\right), \left(A^{1/2}, A^0, A^{3/2}\right), \left(A^0, A^+, A^-\right), \left(A_{\pi^+n}, A_{\pi^-p}, A_{\pi^0p}, A_{\pi^0n}\right)$$

$$A_{\pi^+n} = \sqrt{2}\left(A^- + A^0\right) = \sqrt{2}\left(A_p^{1/2} - \tfrac{1}{3}A^{3/2}\right) = \sqrt{2}\left(A^0 + \tfrac{1}{3}A^{1/2} - \tfrac{1}{3}A^{3/2}\right)$$

$$A_{\pi^-p} = -\sqrt{2}\left(A^- - A^0\right) = \sqrt{2}\left(A_n^{1/2} + \tfrac{1}{3}A^{3/2}\right) = \sqrt{2}\left(A^0 - \tfrac{1}{3}A^{1/2} + \tfrac{1}{3}A^{3/2}\right)$$

$$A_{\pi^0p} = A^+ + A^0 = A_p^{1/2} + \tfrac{2}{3}A^{3/2} = A^0 + \tfrac{1}{3}A^{1/2} + \tfrac{2}{3}A^{3/2}$$

$$A_{\pi^0n} = A^+ - A^0 = -A_n^{1/2} + \tfrac{2}{3}A^{3/2} = -A^0 + \tfrac{1}{3}A^{1/2} + \tfrac{2}{3}A^{3/2}$$

Further details can be found in D. Drechsel and L. Tiator, J. Phys. G 18 (1992) 449-497. (scanned version)

Type of the multipoles: ○ (p(1/2), n(1/2), 3/2) ○ (1/2, 0, 3/2) ○ (0, +, -) ◉ charge channels

Choose pion angular momentum l : [1] ☑ El+ ☐ El- ☐ Ml+ ☐ Ml- ☑ Ll+ ☐ Ll- ☐ Sl+ ☐ Sl-

Reduced multipoles: ☐

Choose kinematical variables

choose an independent (running) variable: ◉ Q^2 ○ W

choose values for Q^2, W, step size and maximum value:

Q^2 $(GeV/c)^2$	W (MeV)	increment	upper value	click here	
0	1080	0.01	0.1	Calculate	Reset

Change of model parameters:

Multipoles

```
               C h M A I D  2 0 1 2
            M. Hilt, S. Scherer, L. Tiator
        Institut fuer Kernphysik, Universitaet Mainz
      *************************************************

 Pion angular momentum l= 1

 All multipoles are given in 10^-3/Mpi+

                W = 1080.000 (MeV)
                ******************
  .3028  1.2695   .0924 13.2100                                       e,gA,F[GeV],gpiN=gA*mp/F
-1.0920 -1.2160  4.3370 -4.2600                                       d8,d9,d20,d21 [GeV^-2]
 5.2350   .9250  2.2050  6.6290 -4.1030 -2.6540                       e48,e49,e50,e51,e52,e53 [GeV^-3]
-8.2690  -.9250 -1.0350  3.9100 -4.3520 10.5390  2.1200               e67,e68,e69,e70,e71,e72,e73 [GeV^-3]
 9.3420-13.7450                                                       e112,e113 [GeV^-3]
```

Q^2 (GeV/c)^2	E1+(pi0_p) Re	E1+(pi0_p) Im	E1+(pi0_n) Re	E1+(pi0_n) Im	E1+(pi+_n) Re	E1+(pi+_n) Im	E1+(pi-_p) Re	E1+(pi-_p) Im	E(lab) (MeV)	q(cm) (MeV)
.00	-.0479	-.0001	-.0177	-.0002	1.4327	.0001	-1.4755	-.0001		
.01	-.0583	-.0001	-.0171	-.0002	1.4017	.0001	-1.4600	-.0001		
.02	-.0673	-.0001	-.0149	-.0001	1.3364	.0001	-1.4106	-.0001		
.03	-.0754	-.0001	-.0115	-.0001	1.2631	.0001	-1.3536	.0000		
.04	-.0831	-.0001	-.0071	-.0001	1.1903	.0001	-1.2977	.0000		
.05	-.0903	-.0001	-.0020	-.0001	1.1208	.0001	-1.2457	.0000		
.06	-.0973	-.0001	.0039	-.0001	1.0555	.0001	-1.1985	.0000		
.07	-.1040	-.0001	.0104	-.0001	.9944	.0001	-1.1561	.0000		
.08	-.1106	-.0001	.0174	-.0001	.9372	.0001	-1.1183	.0000		
.09	-.1171	-.0001	.0250	-.0001	.8836	.0001	-1.0845	.0000		
.10	-.1234	-.0001	.0331	-.0001	.8332	.0001	-1.0545	.0000		

Q^2 (GeV/c)^2	L1+(pi0_p) Re	L1+(pi0_p) Im	L1+(pi0_n) Re	L1+(pi0_n) Im	L1+(pi+_n) Re	L1+(pi+_n) Im	L1+(pi-_p) Re	L1+(pi-_p) Im	E(lab) (MeV)	q(cm) (MeV)
.00	-.0393	-.0001	-.0168	-.0001	.7782	.0000	-.8101	.0000		
.01	-.0440	-.0001	-.0169	-.0001	.6088	.0000	-.6471	.0000		
.02	-.0468	.0000	-.0162	-.0001	.4781	.0000	-.5214	.0000		
.03	-.0486	.0000	-.0151	.0000	.3797	.0000	-.4271	.0000		
.04	-.0496	.0000	-.0138	.0000	.3047	.0000	-.3554	.0000		
.05	-.0501	.0000	-.0124	.0000	.2465	.0000	-.2998	.0000		