New Analysis of Threshold Photoproduction Data from MAMI

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What for?

- Spontaneous Chiral Symmetry Breaking
- Testing ChPT we test QCD in the low-energy regime
- i.e. Chiral Symmetry predicts:
  - Soft S wave in neutral pion photoproduction. Vanishes in the chiral limit so that its value at threshold is explicitly chiral symmetry breaking
  - Strong P wave close to threshold
Pion Photoproduction

- A2 and CB-TAPS collaborations at MAMI
- In the near-threshold region
- High accuracy
- Polarized photons
- LH2 target
- First measurements of photon asymmetry depending on the energy

\[ \sigma = \frac{d\sigma}{d\Omega} \]

\[ \Sigma \equiv \frac{(\sigma_\perp - \sigma_\parallel)}{(\sigma_\perp + \sigma_\parallel)} \]

\[ \vec{\gamma}p \rightarrow \pi^0 p \]

Fig. ripped off from Zehr et al. EPJA48 (2012) 98
Single-Energy Multipoles

- We need up to D waves
- Single-energy extraction of S and P waves
- Dependencies:
  - $\text{Im } P_1 = 0$
  - $\text{Im } E_{0+}$ fixed through unitarity
  - D waves = Born Terms

Hornidge *et al.*, PRL111 (2013) 062004
Single-Energy Multipoles

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Single-Energy Multipoles

- We need up to D waves
- Single-energy extraction of S and P waves
- Dependencies:
  - $\text{Im } P = 0$
  - $\text{Im } E_{0+}$ fixed through unitarity
- D waves under control

Hornidge et al., PRL111 (2013) 062004
Single-Energy Multipoles

- We need up to D waves
- Single-energy extraction of S and P waves
- Dependencies:
  - $\text{Im } R = 0$
  - $\text{Im } E_{0^+}$ fixed through unitarity
  - D waves = Born Terms
- First model-independent extraction of the S and P waves

Hornidge et al., PRL111 (2013) 062004
Energy Dependent Multipoles: Empirical Fit

- Taylor expansion in the partial waves + S wave cusp
- Unitarity is respected in the S wave
- 8 parameters (2 per partial wave)
- P waves are real
- D waves: Born terms
- Chiral symmetry is not incorporated in this approach

\[ E_{0+} = E_{0+}^{(0)} + E_{0+}^{(1)} \frac{\omega - m_{\pi^0}}{m_{\pi^+}} + i\beta \frac{q_{\pi^+}}{m_{\pi^+}} \]

\[ P_i/q = \frac{P_i^{(0)}}{m_{\pi^+}} + P_i^{(1)} \frac{\omega - m_{\pi^0}}{m_{\pi^+}^2} ; \ i = 1, 2, 3 \]
ChPT Multipoles

- HBChPT
  - S and P waves up to $O(q^4)$
  - D waves: Born terms
    (up to order $O(q^4)$ another LEC appears in $E_2$, but it can be ignored)
  - 5 LECs fitted to data: 2 associated to the S wave, 3 associated to the P waves

- U-HBChPT (toy)
  - HBChPT with imaginary part of $E_{0+}$ fixed to the unitary value
  - F-R, Bernstein, PLB724 (2013) 253

- RBChPT
  - S, P and D waves up to $O(q^4)$
  - EOMS scheme
  - 5 LECs fitted to data
  - Hilt, Scherer, Tiator, PRC87 (2013) 045204
$\chi^2$/dof depending on max energy/amount of data

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$E_{\gamma}^{\text{max}}$ (MeV)

Amount of experimental data

- Empirical

<table>
<thead>
<tr>
<th>Amount of experimental data</th>
<th>100</th>
<th>127</th>
<th>154</th>
<th>181</th>
<th>208</th>
<th>235</th>
<th>262</th>
<th>289</th>
<th>316</th>
<th>343</th>
<th>370</th>
<th>397</th>
<th>424</th>
<th>451</th>
<th>478</th>
<th>505</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\gamma}^{\text{max}}$</td>
<td>155</td>
<td>160</td>
<td>165</td>
<td>170</td>
<td>175</td>
<td>180</td>
<td>185</td>
<td>190</td>
<td>195</td>
<td>200</td>
<td>205</td>
<td>210</td>
<td>215</td>
<td>220</td>
<td>225</td>
<td>230</td>
</tr>
</tbody>
</table>

- $\chi^2$/dof
$\chi^2$/dof depending on max energy/amount of data

$E_{\gamma}^{\text{max}}$ (MeV)

Amount of experimental data

Empirical
HBChPT
U-HBChPT
BChPT
$\chi^2$/dof depending on max energy/amount of data

\begin{figure}
\centering
\begin{tikzpicture}
\begin{axis}
[\
    xlabel={$E_{\gamma}^{\text{max}}$ (MeV)},
    ylabel={$\chi^2$/dof},
    xtick={155,160,165,170,175,180,185,190,195},
    ytick={1,1.5,2,2.5,3,3.5,4},
    xticklabels={155,160,165,170,175,180,185,190,195},
    yticklabels={1,1.5,2,2.5,3,3.5,4},
    legend pos=north west,
]
\addplot[\
    color=blue,
    dashed,\
    mark=square,\
] coordinates {\
    (155,1) (160,1.2) (165,1.5) (170,1.8) (175,2.1) (180,2.4) (185,2.7) (190,3.0) (195,3.3)
};
\addplot[\
    color=red,
    dotted,\
    mark=triangle,\
] coordinates {\
    (155,1) (160,1.2) (165,1.5) (170,1.8) (175,2.1) (180,2.4) (185,2.7) (190,3.0) (195,3.3)
};
\addplot[\
    color=green,
    dashdotted,\
    mark=x,\
] coordinates {\
    (155,1) (160,1.2) (165,1.5) (170,1.8) (175,2.1) (180,2.4) (185,2.7) (190,3.0) (195,3.3)
};
\addplot[\
    color=black,
    dashed,\
    mark=diamond,\
] coordinates {\
    (155,1) (160,1.2) (165,1.5) (170,1.8) (175,2.1) (180,2.4) (185,2.7) (190,3.0) (195,3.3)
};
\legend{Empirical, HBChPT, U-HBChPT, BChPT}
\end{axis}
\end{tikzpicture}
\end{figure}
$\chi^2$/dof depending on max energy/amount of data

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{\(\chi^2/dof\) depending on max energy/amount of data.}
\end{figure}
$\chi^2$/dof depending on max energy/amount of data

![Graph showing $\chi^2$/dof vs. $E_{\gamma}^{max}$ (MeV) with different models: Empirical, HBChPT, U-HBChPT, BChPT. The amount of experimental data is also indicated.]
$\chi^2$/dof depending on max energy/amount of data

- Empirical
- HBChPT
- U-HBChPT
- BChPT

Amount of experimental data
$\chi^2$/dof depending on max energy/amount of data

- Empirical
- HBChPT
- U-HBChPT
- BChPT

$E^\text{max}_\gamma$ (MeV)

Amount of experimental data

$\chi^2$/dof
$\chi^2$/dof depending on max energy/amount of data

$E_{\gamma}^{max}$ (MeV) vs. $\chi^2$/dof

- Empirical
- HBChPT
- U-HBChPT
- BChPT

Amount of experimental data
\[ \chi^2/\text{dof depending on max energy/amount of data} \]

\[ \chi^2/\text{dof} \]

- Empirical
- HBChPT
- U-HBChPT
- BChPT

\[ E^\text{max}_\gamma \text{ (MeV)} \]

Amount of experimental data
$\chi^2$/dof depending on max energy/amount of data

$E_{\gamma}^{\text{max}}$ (MeV)

Amount of experimental data
Parameters of the Empirical Fit

- Empirical $\chi^2$/dof is stable & constant params.
Parameters of the Empirical Fit

- Empirical $\chi^2$/dof is stable & constant params.

You can fit up to 170 MeV and the extrapolation up to 185 MeV is safe.
LECs (HBChPT)
Results

- Successfully extracted S and P waves
- Notice how small is $E_{1+}$
- Chiral Perturbation Theory without $\Delta$ works up to 170 MeV (Both Relativistic and Heavy Baryon)
- While empirical fit works up to 185 MeV

Hornidge et al., PRL111 (2013) 062004
Non-Exhaustive Comparison to Theoretical Predictions
• Bonn-Gatchina (BoGa)
  Anisovich, Sarantsev, Bartholomy, Klempt, Nikonov, Thoma, EPJA25 (2005) 427
  http://pwa.hiskp.uni-bonn.de

• Dubna-Mainz-Taipei (DMT)
  Kamalov, Yang, Drechsel, Tiator, PRC64 (2001) 032201
  http://wwwkph.kph.uni-mainz.de/MAID//dmt

• Dispersive Effective Field Theory (GL)
  A. Gasparyan, M.F.M. Lutz, NPA848 (2010) 126

• SAID SN11 solution (SAID)
  http://gwdac.phys.gwu.edu
S Wave

$\text{Re} E_{0+} (10^{-3}/m_{\pi}^{2})$

Predictions: Solid
- GL
- DMT
- BoGa
- SAID

Fits: Dashed
- Empiric
- RBChPT
- HBChPT

D-wave uncertainty
**P waves**

- Errors in the multipoles are very small
- $E_{1+}$ small

⇒ Provide a stringent constrain for the theory

No D-wave uncertainty
Summary

- Best data ever. First measurement of the energy dependence of the photon asymmetry.
- S- and P-waves energy dependence obtained (D waves set to Born terms) ➞ S wave soft due to chiral symmetry.
- Empirical fit goes well up to 185 MeV.
- HBChPT and RBChPT fine up to 165-170 MeV.
- Unitarity is not responsible for the breakdown of ChPT.
- Above 170 MeV: Try the Δ(1232).
- Calculations in the resonance region provide a nice description of the near-threshold region but there is room for improvement.
Future Data in the Pipeline

- F asymmetry $\Rightarrow$ S wave and D waves effects
- T asymmetry $\Rightarrow$ Im $E_{0^+}$ $\Rightarrow$ Unitarity
- Cross section for $\pi^+$ production
- T asymmetry for $\pi^+$
- Isospin dependence of the multipoles
FUTURE

- HBChPT with $\Delta(1232)$
- RBChPT with $\Delta(1232)$
- Calculations in the resonance region have extra info to fix the background
- Measure E asymmetry to pin down D waves