Extracting Chiral Perturbation Theory Parameters from Primakoff Measurements at COMPASS

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Chiral Perturbation Theory (ChPT)

- QCD the true theory of strong interaction
- Perturbation theoretical series $f(\alpha_S) = c_0 + c_1 \alpha_S + c_2 \alpha_S^2 + \cdots$ fails for $\alpha_S \sim 1$.
- Expansion in powers of $\alpha_S$ no longer applicable when $\alpha_S \sim 1$ to obtain predictions => not applicable for bound states => Effective Theory (ChPT)
  - At low $Q$: Effective degrees of freedom $\pi, \eta, K$
  - Expansion not in $\alpha_S$, but in quark masses and momenta of interacting particles
  - Systematic way to calculate corrections: loop, 2-loop, etc.
  - Basic predictions: interactions and properties of pseudoscalar mesons

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Example: $\pi\pi$-scattering

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Dichotomous character of the pion

1. Pion as the lightest bound state of \( q\bar{q} \) in QCD
2. Pion as Nambu-Goldstone boson of the dynamically broken chiral symmetry (DCSB)  
   \( \Rightarrow \) DCSB for low mass of pion
Pion polarizability

• Classically: structure-dependent response to electromagnetic field (due to non-point-like)
• Well-known for atoms and molecules
• Measured on 10%-level for nucleons
• At quantum level: correction to Compton cross-section $\gamma \pi \rightarrow \gamma \pi$
• ChPT (2-loop) prediction:

\[
\alpha_\pi = 2.93 \pm 0.5 \\
\beta_\pi = -2.77 \pm 0.5
\]
Primakoff reactions

• Idea dates back to Henry Primakoff ("photon target")

• Photon is provided by the strong Coulomb field of a nucleus (typical field strength at $d = 5R_{Ni}$: $E \approx 300$ kV/fm

• Coulomb field of nucleus as a source of quasi-real ($P_\gamma^2 \ll m_\pi^2$) photons

• Large impact parameters (ultra-peripheral scattering)
Weizsäcker-Williams approximation

- Coulomb field of relativistic charge \( \approx \) flux of quasi-real photons:

\[
\frac{d\sigma}{ds \, dQ^2 \, d\Phi_n} = \frac{Z^2 \alpha}{\pi(s - m^2_{\pi})} F^2(Q^2) \frac{Q^2 - Q^2_{\text{min}}}{Q^4} \cdot \frac{d\sigma_{\pi\gamma \rightarrow x}}{d\Phi_n}
\]

Form factor

(assuming 1-photon exchange) Flux of quasi-real photons Cross-section of reaction
Weizsäcker-Williams approximation

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\[
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\]

- Particles scatter off equivalent photons

- Peak at tiny momentum transfers \( Q^2 \approx 10^{-5} \text{GeV}^2/c^2 \)
General requirements for Primakoff

• Fixed target setup with nuclear target ($Z$-dependence of WW approximation)
• Good $q^2$-resolution to separate Coulomb processes (Primakoff) from other processes (strong processes)
• Neutral particles in final state $\rightarrow$ calorimetry with good position/energy resolution for good $q^2$-resolution.
• Beam and final state particle ID
• Selection of target material and beam energy to improve the separation of Primakoff events from background
World data before COMPASS

GIS’06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006), plots: T. Nagel, PhD Fil’kov analysis objected by Pasquini, Drechsel, Scherer PRC81, 029802 (2010)
COMPASS overview

COMPASS

Common
Muon
Proton
Apparatus for
Structure and
Spectroscopy

LHC

COMPASS

SPS
COMPASS overview

CERN SPS: protons ~400 GeV (5-10 sec spills)

• Secondary $\pi, K, p$: up to $2 \cdot 10^7 / s$ (typ $5 \cdot 10^6 / s$)
  Nov 2004, 2008-09, 2012:
    hadron spectroscopy & Primakoff reactions

• Tertiary muons: $4 \cdot 10^7 / s$
  2002-04, 2006-07, 2010-11:
    spin structure of the nucleon
Experimental setup

Fixed target experiment

- two stage magnetic spectrometer
- High-precision, high-rate tracking, PID, calorimetry

Setup in 2009
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Runs with hadron beams
- 190 GeV $\pi^-$-beam on $p$ and nuclear targets (C, Ni, W, Pb)
- Silicon microstrip detectors for vertexing
- Recoil and ECAL triggers

Setup in 2009
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Fixed target experiment

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Access to $\pi + \gamma$ reactions:

$$\pi^- + \gamma \rightarrow \begin{cases} 
\pi^- + \gamma \\
\pi^- + \pi^0 / \eta \\
\pi^- + \pi^0 + \pi^0 \\
\pi^- + \pi^- + \pi^+ \\
\pi^- + \pi^- + \pi^+ + \pi^- + \pi^+ \\
\pi^- + \ldots
\end{cases}$$

Runs with hadron beams

• 190 GeV $\pi^-$-beam on $p$ and nuclear targets (C, Ni, W, Pb)
• Silicon microstrip detectors for vertexing
• Recoil and ECAL triggers
• 190 GeV negative hadron beam: 96.8% $\pi^-$, 2.4% $K^-$, 0.8% $\bar{p}$

• Beam particle identification by Cherenkov detectors

• 4mm Ni target disk ($\approx 25\% X_0$)

• Measure scattered $\pi^-$ and produced photons (number of photons depends on final state)

• Select exclusive events at very low $Q^2$

• For absolute cross-section measurements: Luminosity
  
  Luminosity determination via free Kaon decays
  
  $$(K^- \to \pi^-\pi^0 \text{ or } K^- \to \pi^-\pi^0\pi^0)$$
• Identify exclusive reactions $\gamma\pi \rightarrow \gamma\pi$ at smallest momentum transfer $Q^2 < 0.0015 \text{ GeV}^2/c^2$.

Extracting the pion polarizability


Counts / 250 MeV

Counts / 2.74 MeV/c

$\pi^-\text{Ni} \rightarrow \pi^-\gamma\text{Ni}$

Data

Simulation (normalised)

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Data

Simulation (normalised)
• Identify exclusive reactions $\gamma\pi \rightarrow \gamma\pi$ at smallest momentum transfer $Q^2 < 0.001 \text{ GeV}^2/c^2$

• Assuming $\alpha_\pi + \beta_\pi = 0$, from the cross-section

$$R = \frac{\sigma(x_\gamma)}{\sigma_{\alpha_\pi=0}(x_\gamma)} = \frac{N_{\text{meas}}(x_\gamma)}{N_{\text{sim}}(x_\gamma)} = 1 - \frac{3}{2} \cdot \frac{m_\pi^3}{\alpha} \cdot \frac{x_\gamma^2}{1 - x_\gamma} \alpha_\pi$$

can be derived, depending on $x_\gamma = E_\gamma(\text{lab})/E_{\text{beam}}$

• Control systematics by reaction:

$$\mu\gamma \rightarrow \mu\gamma$$
Result for the pion polarizability

\[ \alpha_\pi = (2.0 \pm 0.6_{\text{stat}}) \times 10^{-4} \text{ fm}^3 \]

(assuming \( \alpha_\pi = -\beta_\pi \))

"false polarisability" from muon data:

\[ (0.5 \pm 0.5_{\text{stat}}) \times 10^{-4} \text{ fm}^3 \]

The COMPASS result is in significant tension with the earlier measurements of the pion polarizability.

The expectation from ChPT is confirmed within the uncertainties.
Discovery of the Chiral Anomaly

- Early 60ies: Partially Conserved Axial Current (PCAC):
  \[ \tau_{PCAC}(\pi^0) \approx 0.95 \cdot 10^{-13}\text{s} \]

- 1960 - 1963: First definitive, high energy measurements of the \( \pi^0 \)-lifetime. E.g. with an 18 GeV proton beam at CERN:
  \[ \tau(\pi^0) = (0.95 \pm 0.15) \cdot 10^{-16}\text{s}^* \]

- Adler, Bell, Jackiw, Bardeen 1969: calculation of triangle diagram

  \[ \tau_{anom}(\pi^0) \approx 0.838 \cdot 10^{-16}\text{s} \]

  \( \Rightarrow \) non-conservation of the axial current

A. M. Bernstein and Barry R. Holstein
Rev. Mod. Phys. 85, 49 (2013)

• $F_{3\pi}$: Direct coupling of $\gamma$ to $3\pi$ - process proceeds primarily via the chiral anomaly => one of the most definitive tests of low-energy QCD

• Soft pion limit: $A(\gamma \to \pi\pi\pi) = 0$ (conservation of angular momentum)

• ChPT prediction in chiral limit:

$$F_{3\pi} = \frac{eN_C}{12\pi^2F_{\pi}^3} = (9.78 \pm 0.05) \text{GeV}^{-3}$$

• ChPT corrections due to small masses of quarks:

$$\rightarrow F_{3\pi} = F_{3\pi}(s, t, u)$$

$(s, t, u$-dependence)$

• Accessible in Primakoff reactions via:

$$\pi^-\gamma^* \rightarrow \pi^-\pi^0$$
Radiative width of $\rho$-meson

- Pomeron exchange forbidden by $g$-Parity $\Rightarrow$ clean Primakoff signal (except $\omega/\pi$-exchange)

- Coherent background of $\rho(770)$-production (strong and electro-magnetic)

  Interference between Chiral Anomaly and $\rho(770)$ $\Rightarrow$ possibility of extraction of radiative width of $\rho$-meson
  $\Gamma_{(\rho\rightarrow\pi\gamma)}/\Gamma_{\text{tot}} \approx 4.5 \cdot 10^{-4}$

- $m_{\pi^0}$ distribution shows contribution from $\rho(770)$.

  At kinematic threshold: non-resonant behaviour but chiral anomaly
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Chiral Anomaly:

Ametller, L. et al. Phys.Rev. D64 (2001) 094009 from Serpukhov experiments:

- Using extrapolation & em corr:
  \[ F_{3\pi} = (10.7 \pm 1.2) \text{ GeV}^{-3} \]
- Compare to prediction from ChPT and Chiral Anomaly:
  \[ F_{3\pi} = (9.78 \pm 0.05) \text{ GeV}^{-3} \]

Precision of previous measurements: \( \mathcal{O}(10\%) \)

⇒ More precise experimental determination desirable

Radiative width of \( \rho \)-meson:


- From fit of \( d\sigma/dt \) for \( \rho \) production:
  \[ \Gamma(\rho \to \pi\gamma) = (81 \pm 4 \pm 4) \text{ keV} \]
Final State: $\pi^- \pi^0$

- Dispersive framework to deduce $F_{3\pi}$ from a fit to the full data set up to 1.2 GeV including the $\rho(770)$-resonance:

  Hoferichter, Kubis, and Sakkas  

$$\sigma(s) = \frac{(s - 4M_\pi^2)^3}{1024\pi\sqrt{s}} \left( \int_{-1}^{1} dz \ (1 - z^2)|F(s,t,u)|^2 \right)$$

with $F(s,t,u) = C_2^{(1)} F_2^{(1)}(s,t,u) + C_2^{(2)} F_2^{(2)}(s,t,u)$

Two fit parameters Determinable iteratively

$$C_2^{(1)} = 11.1 \text{ GeV}^{-3}; C_2^{(2)} = 25.5 \text{ GeV}^{-5}$$
$$C_2^{(1)} = 9.4 \text{ GeV}^{-3}; C_2^{(2)} = 20.7 \text{ GeV}^{-5}$$
Fit to the data

- Fit of the final normalized and acceptance-corrected mass-distribution with subtracted background

*preliminary*

- Fit of the theoretical model in good agreement with data
- Statistical uncertainty $\mathcal{O}(1\%)$
- Result to be expected within the next months
• ChPT and DCSB well established in QCD (pion in as Nambu-Goldstone boson)

• Measurement of the pion polarizability at COMPASS
  • Via Primakoff process, COMPASS has determined
    \[ \alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4} \text{fm}^3 \]
  • Most precise experimental determination
  • Systematic control via \( \mu \gamma \rightarrow \mu \gamma \)

• Measurement of the Chiral Anomaly via \( F_{3\pi} \) and the radiative width of the \( \rho \)-meson upcoming
  • Using the Primakoff reaction \( \pi^- \gamma^* \rightarrow \pi^- \pi^0 \) and a full fit to the \( m_{\pi^- \pi^0} \)-spectrum up to 1.2 GeV from a dispersive model
  • Statistical uncertainties expected to be \( \mathcal{O}(1\%) \)

• Other related channels at COMPASS:
  \[
  \begin{aligned}
  \pi^- \gamma^* &\rightarrow \pi^- \pi^0 \pi^0 \\
  \pi^- \gamma^* &\rightarrow \pi^- \pi^- \pi^+
  \end{aligned}
  \]
  chiral tree and loop predictions available