Results and prospects for low-energy QCD processes from COMPASS

Jan Friedrich

Physik-Department, TU München

COMPASS collaboration

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COMPASS Muon and Proton Apparatus for Structure and Spectroscopy
CERN SPS: protons $\sim$ 400 GeV (5 – 10 sec spills)

- secondary $\pi, K, (\bar{p})$: up to $2 \cdot 10^7$/s (typ. $5 \cdot 10^6$/s)
- tertiary muons: $4 \cdot 10^7$/s
  - 2002-04, 2006-07, 2010-11: spin structure of the nucleon
Fixed-target experiment

- two-stage magnetic spectrometer
- high-precision, high-rate tracking, PID, calorimetry
Fixed-target experiment

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- 190 GeV $\pi^-$ beam on $p$ and nuclear targets (C, Ni, W, Pb)
- Silicon microstrip detectors for “vertexing”
- recoil and (digital) ECAL triggers
Electromagnetic Polarisabilities

- structure-dependent response to outer e.m. fields:
  \[ \Delta H = -\frac{1}{2} \left( \alpha \cdot \vec{E}^2 + \beta \cdot \vec{B}^2 \right) \]

- well-known for atoms and molecules
- measured on 10%-level for nucleons (also spin dependent)
Pion polarisability and ChPT

Pion polarisabilities $\alpha_\pi$, $\beta_\pi$ in units of $10^{-4}$ fm$^3$

size of the pion $\sim 1$ fm$^3$ [cf. atoms: polarisability $\approx$ size $\approx 1$ Å$^3$]

Theory: ChPT (2-loop) prediction:

\[
\alpha_\pi - \beta_\pi = 5.7 \pm 1.0
\]
\[
\alpha_\pi + \beta_\pi = 0.16 \pm 0.1
\]

experiments for $\alpha_\pi - \beta_\pi$ lie in the range $4 \cdots 14$

($\alpha_\pi + \beta_\pi = 0$ assumed)

ChPT: chiral perturbation theory: low-energy expansion of QCD
Pion polarisability and ChPT

pion polarisabilities $\alpha_\pi$, $\beta_\pi$ in units of $10^{-4}$ fm$^3$

Theory: ChPT (2-loop) prediction:

\[
\begin{align*}
\alpha_\pi &= 2.93 \pm 0.5 \\
\beta_\pi &= -2.77 \pm 0.5
\end{align*}
\]

input to theory: measurement of the radiative $\pi^- \rightarrow e^- \nu_e \gamma$ decay

PIBETA experiment at PSI, PRL 103 (2009) 051802

experiments for $\alpha_\pi$ lie in the range $2 \cdots 7$
Pion Compton Scattering

\[ \pi \gamma \rightarrow \pi \gamma \]

- Two kinematic variables, in CM: total energy \( \sqrt{s} \), scattering angle \( \theta_{cm} \)

\[
\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2 (s^2 z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha m_\pi^3 (s - m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathcal{P}
\]

\[
\mathcal{P} = z_-^2 (\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+ (\alpha_\pi + \beta_\pi) - \frac{(s - m_\pi^2)^2}{24s} z_-^3 (\alpha_2 - \beta_2)
\]

\[
z_\pm = 1 \pm \cos \theta_{cm}
\]
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Pion Compton scattering: embedding the process

Primakoff processes

Radiative pion photoproduction

Photon-Photon fusion
Pion polarisability: world data before COMPASS

Primakoff processes

Radiative pion photoproduction

Photon-Photon fusion

GIS’06: ChPT prediction, Gasser, Ivanov, Sainio, NPB745 (2006), plots: T. Nagel, PhD
Fil’kow analysis objected by Pasquini, Drechsel, Scherer PRC81, 029802 (2010)
- high-energetic pion beam on 4mm nickel disk
- observe scattered pions in coincidence with produced hard photons with energy fraction $x_\gamma = E_\gamma / E_{\text{beam}}$
- study the cross-section shape
Extraction of the pion polarisability

- Identify exclusive reactions

\[ \pi \gamma \{ \text{Ni} \rightarrow \text{Ni}' \} \rightarrow \pi \gamma \]

at smallest momentum transfer \( < 0.001 \text{ GeV}^2/c^2 \)

- Assuming \( \alpha_\pi + \beta_\pi = 0 \), from the cross-section

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

is derived, depending on \( x_\gamma = E_{\gamma(\text{lab})}/E_{\text{Beam}} \).

Measuring \( R \) the polarisability \( \alpha_\pi \) can be concluded.

- Depends on MC simulation of the acceptance, control systematics by

\[ \mu \gamma \{ \text{Ni} \rightarrow \text{Ni}' \} \rightarrow \mu \gamma \]

and

\[ K^- \rightarrow \pi^- \pi^0 \rightarrow \pi \gamma \gamma \]
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Charged pions traverse the nuclear **electric field**
- typical field strength at $d = 5R_{Ni}$: $E \approx 300 \text{ kV/fm}$

**Bremsstrahlung process:**
- particles scatter off **equivalent photons**
- tiny momentum transfer $Q^2 \approx 10^{-5} \text{ GeV}^2/c^2$
- pion/muon (quasi-)real Compton scattering

**Polarisability contribution**
- Compton cross-section typically diminished
- corresponding charge separation $\approx 10^{-5} \text{ fm} \cdot e$
Polarisability effect in Primakoff technique

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Pion/muon (quasi-)real Compton scattering

Polarisability contribution
- Compton cross-section typically diminished
  - corresponding charge separation
    - $\approx 10^{-5} \text{ fm} \cdot e$
Principle of the measurement

- Spatial resolution of tracks $\sim 10\mu m$
- Angular resolution of photons $\sim 30\mu rad$

Diagram showing the layout of ECAL1, CEDARs, SM1, SM2, ECAL2, C/Ni/W targets, and silicon stations.
ECAL2: 3000 cells of different types
Figure 3.5: Profile of energy deviations shown for 1/4 of a shashlik block and for muon data photons within the range $133 \text{ GeV} < E_\gamma < 152 \text{ GeV}$.

Figure 3.6: Technical drawing of a full shashlik cell to be compared with the figure to the left.

from: Th. Nagel, PhD thesis TUM 2012
Measurement of the Charged-Pion Polarizability

C. Adolph, R. Akhunzhanov, M. G. Alexeev, G. D. Alexeev, A. Amoroso, V. Andrieux, V. Anosov,

... [213 authors]

(COMPASS Collaboration)

(Received 2 June 2014; revised manuscript received 24 December 2014; published 10 February 2015)

The COMPASS collaboration at CERN has investigated pion Compton scattering, \( \pi^- \gamma \rightarrow \pi^- \gamma \), at center-of-mass energy below 3.5 pion masses. The process is embedded in the reaction \( \pi^- \text{Ni} \rightarrow \pi^- \gamma \text{Ni} \), which is initiated by 190 GeV pions impinging on a nickel target. The exchange of quasireal photons is selected by isolating the sharp Coulomb peak observed at smallest momentum transfers, \( Q^2 < 0.0015 \text{ (GeV/c)}^2 \). From a sample of 63 000 events, the pion electric polarizability is determined to be \( \alpha_x = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4} \text{ fm}^3 \) under the assumption \( \alpha_x = -\beta_x \), which relates the electric and magnetic dipole polarizabilities. It is the most precise measurement of this fundamental low-energy parameter of strong
Identifying the $\pi \gamma \rightarrow \pi \gamma$ reaction


- Energy balance $\Delta E = E_\pi + E_\gamma - E_{\text{Beam}}$
- Exclusivity peak $\sigma \approx 2.6$ GeV (1.4%)
- $\sim 63.000$ exclusive events ($x_\gamma > 0.4$) (Serpukhov $\sim 7000$ for $x_\gamma > 0.5$)
Primakoff peak

\[ |Q| \ [	ext{GeV/c}] \]
\[ 0 \quad 0.05 \quad 0.1 \quad 0.15 \quad 0.2 \quad 0.25 \quad 0.3 \]
\[ \text{counts / 2.74 MeV/c} \]

\[ \text{Ni}^\gamma \rightarrow \pi^- \text{Ni} \rightarrow \pi^- \gamma \text{Ni} \]

- \( \Delta Q_T \approx 12 \text{ MeV/c} \) (190 GeV/c beam \( \rightarrow \) requires few-\( \mu \text{rad} \) angular resolution)
- first diffractive minimum on Ni nucleus at \( Q \approx 190 \text{ MeV/c} \)
- data a little more narrow than simulation \( \rightarrow \) negative interference?
Primakoff peak: muon data


- muon control measurement: pure electromagnetic interaction
- e.m. nuclear effects well understood
Photon energy spectra for muon and pion beam

Pion polarisability: COMPASS result

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

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

“false polarisability” from muon data:

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

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<thead>
<tr>
<th>source of systematic uncertainty</th>
<th>estimated magnitude</th>
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$\alpha_\pi = (2.00 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4} \text{ fm}^3$
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COMPASS result for the pion polarisability:

\[
\alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4} \text{ fm}^3
\]

with $\alpha_\pi = -\beta_\pi$ assumed
The new COMPASS result is in significant tension with the earlier measurements of the pion polarisability.

The expectation from ChPT is confirmed within uncertainties.
Theory aspects of the $\pi^-$ polarisability measurement

- Radiative corrections (Compton scattering part)


- Higher order pion dynamics: Dispersion relations vs. ChPT (B. Pasquini, OK)
- Pion polarisability from lattice QCD: first studies indicate small value (large uncertainty)
Access to $\pi \gamma$-initiated reactions via the Primakoff effect

\[ \pi^- + \gamma \rightarrow \left\{ \begin{array}{l} \pi^- + \gamma \\ \pi^- + \pi^0 / \eta \\ \pi^- + \pi^0 + \pi^0 \\ \pi^- + \pi^- + \pi^+ \\ \pi^- + \pi^- + \pi^+ + \pi^- + \pi^+ \\ \pi^- + ... \end{array} \right. \]

analogously: Kaon-induced reactions $K^- + \gamma \rightarrow \cdots$
Chiral anomaly in $\pi^- \gamma \rightarrow \pi^- \pi^0$

- contributions from chiral anomaly $F_{3\pi}$ and the $\rho(770)$ resonance
- can be described by a dispersive method $\rightarrow$ increased sensitivity to the chiral anomaly
- uncertainty estimate $< 1\%$

*Hoferichter et al., PRD86 (2012) 116009*
Chiral dynamics in $\pi\gamma \rightarrow 3\pi$

**relevant physics:** pion scattering lengths, pion loop contributions

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**Published in PRL 108 (2012) 192001**

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**Normalization:** analysis ongoing
Radiative Coupling of $a_2(1320)$ and $\pi_2(1670)$

$\Gamma_0(a_2(1320) \to \pi\gamma) \propto M2$

$\Gamma_0(\pi_2(1670) \to \pi\gamma) \propto E2$

$\Leftrightarrow$ meson wave functions: $\Gamma_{i \to f} \propto |\langle \psi_f | e^{-i \vec{q} \cdot \vec{r}} \hat{\epsilon} \cdot \vec{p} | \psi_i \rangle|^2$

- normalization via beam kaon decays
- large Coulomb correction

*published in EPJ A50 (2014) 79*
Measurement of the pion polarisability at COMPASS
  via the Primakoff reaction, COMPASS has determined

\[ \alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4} \text{fm}^3 \]

- most direct access to the \( \pi\gamma \rightarrow \pi\gamma \) process
- most precise experimental determination
- control of systematics: \( \mu\gamma \rightarrow \mu\gamma, \ K^- \rightarrow \pi^-\pi^0 \)

Related topics at COMPASS: radiative widths and chiral dynamics in \( \pi^-\gamma \rightarrow \pi^-\pi^0 \) and \( \pi\gamma \rightarrow \pi\pi\pi \) reactions
  - chiral anomaly coming soon

High-statistics run 2012
  - separate determination of \( \alpha_\pi \) and \( \beta_\pi \)
  - \( s \)-dependent quadrupole polarisabilities
  - First studies for a kaon polarisability measurement
More channels of interest for low-energy QCD

- Primakoff reaction with $\pi^- \eta$ final state
- $\pi^0$ lifetime

Mid-term future perspectives with conventional beams

- SIDIS on a transversely polarized deuteron target
- Elastic muon-proton scattering at low momentum transfers
- Antiproton-induced hadron spectroscopy
- Polarized-target DVCS and DY processes

Longer-term future ideas with RF-separated beams

- Kaon-induced hadron spectroscopy
- Kaon-induced Drell-Yan processes

principle of RF separation
Thank you for your attention!