Measurement of the Pion Polarisability at COMPASS

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Outline

- Compton scattering and polarisabilities
  - Motivation
  - Related processes for unstable particles
  - Primakoff kinematics

- The COMPASS 2004 pilot hadron run

- Data analysis and preliminary results
How are hadrons built up in terms of their constituents?

Static properties ⇔ form factors
Hadron structure

- How are hadrons built up in terms of their constituents?
  
  **Static properties ⇔ form factors**

- How do hadrons react to (small) external forces?
  
  **Non-pointlike response ⇔ polarisabilities**

**classical**

\[ \vec{d} = (eZ)2\ell = \vec{\alpha}\vec{E} \]

\[ K\ell = (eZ)E \]

\[ \vec{\alpha} = \frac{2(eZ)^2}{K} \]
for point-like target completely determined by QED

- polarisability contribution starting at $\mathcal{O}(E\gamma)$ (for spin-$\frac{1}{2}$)
Compton scattering

- for point-like target completely determined by QED
- polarisability contribution starting at $\mathcal{O}(E_\gamma)$ (for spin-$\frac{1}{2}$)

### Nucleon case

- **Born** contributions
- **Resonance** contributions
- **Pion loop**
- **Pion pole**
- **2-pion** contributions
Compton scattering

- for point-like target completely determined by QED
- polarisability contribution starting at $\mathcal{O}(E_\gamma)$ (for spin-$\frac{1}{2}$)

Proton data

$\tilde{\alpha}_p = 12.1 \pm 0.3_{\text{stat}} \pm 0.4_{\text{syst}} \pm 0.3_{\text{mod}} \cdot 10^{-4} \text{fm}^3$

$\tilde{\beta}_p = 1.6 \pm 0.4_{\text{stat}} \pm 0.4_{\text{syst}} \pm 0.4_{\text{mod}} \cdot 10^{-4} \text{fm}^3$

(cancellation of para- and diamagnetic contributions)

(cancellation of para- and diamagnetic contributions)
Compton scattering

- for point-like target completely determined by QED
- polarisability contribution starting at $\mathcal{O}(E\gamma)$ (for spin-$\frac{1}{2}$)

**Pion case**

$$\mathcal{M} = 8\pi i \cdot m_\pi \left[ \left( -\frac{\alpha}{m_\pi} + \bar{\alpha} \cdot \omega_1 \omega_2 \right) \vec{\epsilon}_1 \cdot \vec{\epsilon}_2 + \bar{\beta} \cdot (\vec{q}_1 \times \vec{\epsilon}_1) \cdot (\vec{q}_2 \times \vec{\epsilon}_2) \right]$$

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Meson Polarisabilities

Pion

- Low-energy expansion of QCD: Chiral perturbation theory
  Pion has a special role as the **Goldstone boson** (massless in the chiral limit)
- are the basic features correctly described?
Meson Polarisabilities

Pion

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ChPT 1-loop for $\pi^\pm$

\[
\begin{align*}
\bar{\alpha} + \bar{\beta} &= 0 \\
\bar{\alpha} - \bar{\beta} &= \frac{2e^2}{m_\pi f_\pi^2} (L_9^r + L_{10}^r) \\
&= +5.4 \pm 0.8 \cdot 10^{-4} \text{fm}^3
\end{align*}
\]
Meson Polarisabilities

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ChPT 2-loop for $\pi^\pm$

\[
\bar{\alpha} + \bar{\beta} = 0.3 \pm 0.1 \cdot 10^{-4} \text{fm}^3 \\
\bar{\alpha} - \bar{\beta} = 5.7 \pm 1.0 \cdot 10^{-4} \text{fm}^3
\]
Meson Polarisabilities

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Dispersion sum rules $\pi^\pm$

\[
\bar{\alpha} + \bar{\beta} = 0.39 \pm 0.4 \cdot 10^{-4} \text{fm}^3
\]
\[
\bar{\alpha} - \bar{\beta} \approx 10 \cdot 10^{-4} \text{fm}^3
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Meson Polarisabilities

**Pion**
- Low-energy expansion of QCD: Chiral perturbation theory

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**ChPT 2-loop for** \(\pi^\pm\)
- \(\bar{\alpha} + \bar{\beta} = 0.3 \pm 0.1 \cdot 10^{-4}\text{fm}^3\)
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**Kaon**
- Higher mass \(\Leftrightarrow\) smaller polarisability by a factor \(\sim 5\)
- theoretically very exciting – need for experimental data!
1\textsuperscript{st} option

\textbf{test the particle during its production process}

\textbf{A)} \ e^+e^- \rightarrow e^+e^- \pi^+\pi^- \ (\gamma\gamma \rightarrow \pi^+\pi^-)
1st option

test the particle during its production process

A) $e^+e^- \rightarrow e^+e^- \pi^+\pi^- \quad (\gamma\gamma \rightarrow \pi^+\pi^-)$

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Compton scattering on unstable particles

1st option

- test the particle during its production process

A) \( e^+ e^- \rightarrow e^+ e^- \pi^+ \pi^- \) (\( \gamma \gamma \rightarrow \pi^+ \pi^- \))

B) radiative pion photoproduction on the nucleon

\( \gamma \ p \rightarrow \gamma \ n \ \pi^+ \)
2\textsuperscript{nd} option

use ultra-relativistic particle beam (quasi-stable)

on “photon target”: Coulomb photon of a heavy nucleus participates in (semi-)hadronic interaction – Primakoff effect

\[ Q^2 \ll \]
Pion-nucleus scattering at small $Q^2$

$\pi + Pb \rightarrow X^- + Pb$

diffractive scattering:
→ meson spectroscopy
→ exotics

$Q^2 < 0.001 \text{ GeV}^2/c^2$

- $\pi + \gamma^{(*)} \rightarrow \pi' + \pi^0$
- $\pi + \gamma^{(*)} \rightarrow \pi' + \gamma$

Primakoff reaction
→ pion polarisability
Pion-nucleus scattering at small $Q^2$

\[ \pi + Pb \rightarrow X^- + Pb \]
diffractive scattering:
\[ \rightarrow \text{meson spectroscopy} \]
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Primakoff reaction
\[ \rightarrow \text{pion polarisability} \]

e.m./strong Interference
Recently approached in eikonal approx. (G. Faeldt)
Polarisability Extraction

$E_\gamma$ dependence assuming $\overline{\beta}_\pi + \overline{\alpha}_\pi = 0$

\[
\frac{d\sigma_{\text{Prim}}}{dE_\gamma} = \frac{d\sigma_{pl}}{dE_\gamma} + \frac{d\sigma(\overline{\alpha}_\pi, \overline{\beta}_\pi)}{dE_\gamma} = \frac{d\sigma_{pl}}{dE_\gamma} + \frac{d\sigma(\overline{\beta}_\pi)}{dE_\gamma} = \]

\[
= \frac{4Z^2\alpha^3}{m^2_\pi} \cdot \frac{E_{\pi'}}{E_{\text{Beam}}E_\gamma} \cdot \left( \frac{2}{3} \ln \frac{Q^2_{\text{max}}}{Q^2_{\text{min}}} - \frac{19}{9} + 4\sqrt{\frac{Q^2_{\text{min}}}{Q^2_{\text{max}}}} \right) + \]

\[
+ \frac{4Z^2\alpha^3}{m^2_\pi} \cdot \frac{E_\gamma}{E^2_{\text{Beam}}} \cdot \frac{\overline{\beta}_\pi m^3_\pi}{\alpha} \cdot \left( \ln \frac{Q^2_{\text{max}}}{Q^2_{\text{min}}} - 3 + 4\sqrt{\frac{Q^2_{\text{min}}}{Q^2_{\text{max}}}} \right) \]

\[Q_{\text{min}} = \frac{E_\gamma m^2_\pi}{2E_{\text{Beam}}E_{\pi'}}\]

\[\omega = \frac{E_\gamma}{E_{\text{Beam}}}\]

**Ratio** $R_\pi = \frac{d\sigma_{\text{Prim}}}{d\sigma_{pl}}$

\[R_\pi(\omega) \approx 1 + \frac{3}{2} \cdot \frac{m^3_\pi}{\alpha} \cdot \frac{\omega^2}{1 - \omega} \overline{\beta}_\pi\]
Data on the Pion Polarisability

<table>
<thead>
<tr>
<th></th>
<th>$\alpha + \beta$ [10^{-4} fm^3]</th>
<th>$\alpha - \beta$ [10^{-4} fm^3]</th>
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<tr>
<td>Bürgi/Gasser (ChPT)</td>
<td>0.3 ± 0.1</td>
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<tr>
<td>Mark II CELLO Serpukhov MAMI COMPASS</td>
<td>0.22 ± 0.07 ± 0.04 0.33 ± 0.06 ± 0.01 1.8 ± 3.1 ± 2.5</td>
<td>4.8 ± 1.0 12.3 ± 2.6 11.6 ± 1.5 ± 3.0 ± 0.5</td>
</tr>
</tbody>
</table>

- different reactions with different systematics
- challenging measurements (Mainz ~ 1000 h beam time!)
- no coherent picture of pion polarisability yet
SPS Beam: Protons up to 400 GeV, 4.2s/16.8s spills
secondary hadron beams ($\pi$, $K$, ...)
tertiary muons: $2 \cdot 10^8$/spill with 160 GeV/c, 80% polarisation
Czech Republic, France, Germany, India, Israel, Italy, Japan, Poland, Portugal, Russia, CERN

240 physicists from 28 institutes

Bielefeld, Bochum, Bonn, Burdwan/Calcutta, CERN, Dubna, Erlangen, Freiburg, Lisboa, Mainz, Moscow, Munich, Nagoya, Parg, Protvino, Saclay, Tel Aviv, Torino, Trieste, Warsaw

Data acquisition 2002, 03, 04, 06 with muon beam on polarised LiD target
Oct. 2004: pilot hadron run ($\pi^-$)
The COmmom Muon and Proton Apparatus for Structure and Spectroscopy

2 stage spectrometer
The COmmom Muon and Proton Apparatus for Structure and Spectroscopy

2 stage spectrometer
small area tracking

Silicon microstrips

GEM foil

Micromegas

Measurement of the Pion Polarisability at COMPASS
The COmmom Muon and Proton Apparatus for Structure and Spectroscopy

2 stage spectrometer  
~ 200,000 channels  
small/large area tracking  
particle identification  
~ 50 MB/s DAQ rate

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Measurement of the Pion Polarisability at COMPASS
4 weeks data taking in autumn 2004

190 GeV $\pi^-/\mu^-$-beam, $10^6$ particles/s

Targets: Pb ($X_0 = 0.29, 0.5$), Cu (0.25), C (0.12)
Target region

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Measurement of the Pion Polarisability at COMPASS
Target region

(diffractive $\pi^+\pi^-\pi^-$ vertices)
Primakoff Reaction

**Selection of $\pi^- + \gamma(\ast) \rightarrow \pi^- + \gamma$**

- exactly one primary vertex in the target ($p_{T,\pi^-} > 15$ MeV)
- exactly one $\pi^-$ track of high quality, $E_{\pi^-} < 170$ GeV
- exactly one Ecal2 cluster as photon candidate
- $| E_{\pi^-} + E_\gamma - E_{\text{beam}} | < 25$ GeV
- $Q^2 < 0.0075$ GeV$^2$/c$^2$, $M_{\pi\gamma} < 3.75 m_\pi$

**Background**

- $K^- \rightarrow \pi^- \pi^0$ (empty target subtraction)
- diffractive channels with one high-energetic photon (different $Q^2$ dependence)
Q^2 distribution

COMPASS 2004 π^- data

- Coulomb peak
- Diffractive background
- Empty target background

preliminary
Q^2 distribution for different targets

COMPASS 2004 π⁻ data

events
10^4
10^3
10^2
2+1 mm Pb
3.55 mm Cu
23.5 mm C

preliminary
$Z^2$ dependence of Primakoff cross section

COMPASS 2004 $\pi^-$ data

$\sigma/\sigma_{\text{Pb}}$

-3

-2

-1

1

Pb
Cu
C

preliminary

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Measurement of the Pion Polarisability at COMPASS
\[ \omega = \frac{E_\gamma}{E_{\text{Beam}}} \] dependence of signal and background

COMPASS 2004 $\pi^-$ data

Yields

$N_{\text{measured}}(\omega)$

$B_{\text{diff}}(\omega)$

$B_{\text{empty target}}(\omega)$

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Measurement of the Pion Polarisability at COMPASS
Radiative corrections for $\pi$ and $\mu$ data

\[
\frac{\sigma_{\text{Born}} + \sigma_{\text{corr}}}{\sigma_{\text{Born}}} \quad \omega
\]

\[
0.5 \quad 0.55 \quad 0.6 \quad 0.65 \quad 0.7 \quad 0.75 \quad 0.8 \quad 0.85 \quad 0.9
\]

Vac. pol.  Compton  Screening  SUM

\[
0.9 \quad 0.92 \quad 0.94 \quad 0.96 \quad 0.98 \quad 1 \quad 1.02 \quad 1.04
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Vac. pol.  Compton  Screening  SUM

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\frac{\sigma_{\text{Born}} + \sigma_{\text{corr}}}{\sigma_{\text{Born}}} \quad \omega
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Measurement of the Pion Polarisability at COMPASS
Muon control measurement

COMPASS 2004 $\mu^-$ data

\[ \beta = (-0.2 \pm 0.5_{stat}) \times 10^{-4} \text{ fm}^3 \]

\[ \chi^2/\text{ndf} = 12.2/14 = 0.9 \]

RC included
Measurement of the Pion Polarisability at COMPASS

\[ \alpha_\pi + \beta_\pi = 0 \]

\[ \beta_\pi = (-2.5 \pm 1.7_{\text{stat}}) \times 10^{-4} \text{ fm}^3 \]

\[ \chi^2/\text{ndf} = 16.7/14 = 1.2 \]
# Systematic error estimate

<table>
<thead>
<tr>
<th>Error, $10^{-4}\text{fm}^3$</th>
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<tr>
<td>Setup description in MC ($\mu$ data)</td>
</tr>
<tr>
<td>Diffractive and empty target background subtraction</td>
</tr>
<tr>
<td>Muons background</td>
</tr>
<tr>
<td>Electrons background</td>
</tr>
</tbody>
</table>
From COMPASS data taken in \( \sim 3 \) days of beam time (7300 events), the pion polarisability value

\[
\overline{\beta}_\pi = -2.5 \pm 1.7_{\text{stat}} \pm 0.6_{\text{syst}} \cdot 10^{-4}\text{fm}^3
\]

is extracted (preliminary).

**Outlook**

- Additional data on tape (adjusted MC needed)
- Independent extraction of \( \overline{\alpha}_\pi \) and \( \overline{\beta}_\pi \)
- New improved measurement at COMPASS
Data on the Pion Polarisability

<table>
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<th>Experiment</th>
<th>$\alpha + \beta$ $[10^{-4} \text{ fm}^3]$</th>
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Measurement of the Pion Polarisability at COMPASS
$Q^2$ for muon data

COMPASS 2004 data

preliminary

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Measurement of the Pion Polarisability at COMPASS
Measurement of the Pion Polarisability at COMPASS

COMPASS 2004 data

Acceptance from MC simulation

\[ \text{acceptance}(\omega) \]

\( \omega \)

\( \mu \)

\( \pi \)

preliminary

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Virtual Empty Target Method

COMPASS 2004 $\pi^-$ data

Segmented lead target

Trigger scintillator

Virtual empty target

Preliminary

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Measurement of the Pion Polarisability at COMPASS
Empty target background subtraction

without,

with empty target subtraction

preliminary spectra
2-dimensional $E_\gamma - \theta_\gamma$ raw spectrum

COMPASS 2004 Hadron Run

Theory

with MC-correction

(mainly $\gamma$ conversion, $\pi^-$ decay, Ecal2 beam hole)

$\rightarrow$ determination of $\alpha$ and $\beta$ without $\alpha + \beta = 0$ constraint

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Measurement of the Pion Polarisability at COMPASS
Possible improvements

Analysis

- new production of data
  - alignment
  - vertexing (for z<-100cm)
  - time-dependent Ecal2 calibration
  - retrieve scaler information
- refined Monte Carlo for different settings

New measurement

- CEDAR for incoming particle ID
- stable setup
- optimized material budget