Measurement of the Pion Polarizability at COMPASS

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COMPASS collaboration

Particle Physics Seminar
April 3, 2015
Short story of the pion

- Yukawa 1935: hypothesis of $\sim 100$ MeV massive exchange particle "µ" for the strong interaction between protons and neutrons
- Discovery of muons 1936
Short story of the pion

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  "µ" for the strong interaction between protons and neutrons
- Discovery of muons 1936
- Discovery of pions 1947

NATURE October 4, 1947 Vol. 150
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- 1958: decay \( \pi^+ \rightarrow \mu^+ \nu_\mu \) dominant, small branching \( \pi^+ \rightarrow e^+ \nu_e \)  

\[ \Rightarrow \ V \rightarrow A \ \text{theory of weak interaction} \]
- 1961: Spin-1 mesonic excitation of the pion (\( \rho \)-resonance at BNL)
- 1964: quark hypothesis
- 1966: pion scattering lengths
Short story of the pion

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  \( \Rightarrow \ V - A \) theory of weak interaction
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- 1964: quark hypothesis
- 1966: pion scattering lengths
- ... 
- 1982: first data on the pion polarisability
Measurement of the Charged-Pion Polarizability

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

(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, $\pi^- \gamma \rightarrow \pi^\gamma \gamma$, at center-of-mass energy below 3.5 pion masses. The process is embedded in the reaction $\pi^- \text{Ni} \rightarrow \pi^\gamma \gamma \text{Ni}$, which is initiated by 190 GeV pions impinging on a nickel target. The exchange of quasi-real 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 $\alpha_\pi = (2.0 \pm 0.6^{\text{stat}} \pm 0.7^{\text{syst}}) \times 10^{-4} \text{ fm}^3$ under the assumption $\alpha_\pi = -\beta_\pi$, which relates the electric and magnetic dipole polarizabilities. It is the most precise measurement of this fundamental low-energy parameter of strong
CERN experiment brings precision to a cornerstone of particle physics

11 Feb 2015

Geneva, 11 February 2015. In a paper published yesterday in the journal Physical Review Letters, the COMPASS experiment at CERN\(^1\) reports a key measurement on the strong interaction. The strong interaction binds quarks into protons and neutrons, and protons and neutrons into the nuclei of all the elements from which matter is built. Inside those nuclei, particles called pions made up of a quark and an antiquark mediate the interaction. Strong interaction theory makes a precise prediction on the polarisability of
Intro: Pions & ChPT

COMPASS

Pion polarisability

Summary and Outlook

Press echo in spring 2015

J. M. Friedrich — Pion Polarisability with COMPASS
L'interazione forte dei quark ha meno segreti

L'esperimento COMPASS al CERN fornisce una misura chiave dell'interazione forte.
Press echo in spring 2015
CERN Physicists Measure Polarizability of Pion

Feb 16, 2015 by Sci-News.com

Scientists from CERN's COMPASS collaboration have made the most precise measurement ever of the polarizability of pion – the fundamental low-energy parameter of strong interaction.

An electron (green) hits a proton in a nucleus, creating a pion (green-dotted particle) and transforming the proton into a neutron. Image credit: Joanna Griffin / Jefferson Lab.

Everything we see in the Universe is made up of fundamental particles called...
CERN Physicists Measure Polarizability of Pion

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Scientists from CERN’s COMPASS collaboration have made the most precise measurement ever of the polarizability of pion – a fundamental low-energy parameter of strong interaction.

An electron (green) hits a proton in a nucleus, creating a pion (green; slimmer particle) and transforming the proton into a neutron. Image credit: Joanna Griffin / Jefferson Lab.

Everything we see in the Universe is made up of fundamental particles called
How to understand quark-gluon dynamics?

complicated system of interacting quarks and gluons

ChPT → effective degrees of freedom at low energy: mass, charge, spin, effective (self-)coupling

π only

π - photon

π - π - photon
pion scattering lengths: 2-loop predictions

- \( a_0^0 m_\pi = 0.220 \pm 0.005 \) confirmed by E865 in \( K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e \)
- \( (a_0^0 - a_0^2) m_\pi = 0.264 \pm 0.006 \) confirmed by NA48 in \( K^+ \rightarrow \pi^+ \pi^0 \pi^0 \)

pion polarisability: electric \( \alpha_\pi \), magnetic \( \beta_\pi \)

- contribution to Compton scattering
- ChPT prediction obtained by the relation to \( \pi^+ \rightarrow e^+ \nu_e \gamma \) [Gasser, Ivanov, Sainio, Nucl. Phys. B745, 2006]
  [PIBETA, M. Bychkov et al., PRL 103, 051802, 2009]

\[
\begin{align*}
\alpha_\pi + \beta_\pi &= (0.2 \pm 0.1) \cdot 10^{-4} \text{fm}^3 \\
\alpha_\pi - \beta_\pi &= (5.7 \pm 1.0) \cdot 10^{-4} \text{fm}^3 \\
\alpha_\pi &= (2.9 \pm 0.5) \cdot 10^{-4} \text{fm}^3
\end{align*}
\]

ChPT prediction contradicting the experimental findings (prior to our analysis)
Pion scattering including a real photon

- Leading-order prediction from ChPT
  \( \leftrightarrow \) pion scattering lengths
  combined with photon coupling
- chiral loop contribution
  theory prediction available, no measurement

Chiral anomaly \( F_{3\pi} \)

- established on 10% level
- further development: inclusion of the \( \rho \) resonance
  theoretical work by Kubis, Hoferichter, Sakkas
  PRD86(2012)116009
ChPT prediction for the pion polarisability

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

Compton cross-section contains information about e.m. polarisability (as deviation from the expectation for a pointlike particle)

\[ \text{polarisabilities } \alpha_\pi, \beta_\pi \ [10^{-4} \ \text{fm}^3] \]

ChPT (2-loop) prediction: \( \alpha_\pi - \beta_\pi = 5.7 \pm 1.0 \quad \alpha_\pi + \beta_\pi = 0.16 \pm 0.1 \)

experiments: 4 — 14 \((\beta_\pi \approx -\alpha_\pi \text{ assumed})\)
ChPT prediction for the pion polarisability

\[ \pi^+ + \gamma \rightarrow \pi^+ + \gamma \]

Compton cross-section contains information about e.m. polarisability
(as deviation from the expectation for a pointlike particle)

polarisabilities \( \alpha_\pi, \beta_\pi \) [\(10^{-4}\) fm\(^3\)]

ChPT (2-loop) prediction:

\[ \alpha_\pi = 2.93, \quad \beta_\pi = -2.77 \]

experiments: 2 – 7

\((\beta_\pi \approx -\alpha_\pi\) assumed\)
Steer high-energetic pion beam on a ~4mm nickel disk.
Observe scattered pions in coincidence with produced hard photons.
Measured cross-section shape is linked to pion Compton scattering.
Polarisability effect in Primakoff technique

- Charged pion traversing the nuclear electric field
  - typical field strength at $r = 5R_{Ni}$: $E \sim 300 \text{kV/fm}$

- Bremsstrahlung emission
  - particle scatters 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
  - expected charge separation $\sim 10^{-5} \text{fm} \cdot e$
Charged pion traversing the nuclear **electric** field
- Typical field strength at
- \( E \sim 300 \, \text{kV/fm} \)

Bremsstrahlung emission
- Particle scatters off equivalent photons
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Compton scattering
- Polarisability contribution
- Compton cross-section typically diminished
- Expected charge separation \( \sim 10^{-5} \, \text{fm} \cdot e \)
Pion Compton Scattering

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

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

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

\[
z_\pm = 1 \pm \cos \theta_{cm}
\]

- $\sigma_{tot}(s)$ rather insensitive to pion’s low-energy structure
- Up to 20% effect on backward angular distributions of $d\sigma/d\Omega_{cm}$
Pion Compton Scattering

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

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

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\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2 (s^2 z^2_+ + m^4_\pi z^2_-)}{s(sz_+ + m^2_\pi z_-)^2} - \frac{\alpha m^3_\pi (s - m^2_\pi)^2}{4s^2(sz_+ + m^2_\pi z_-)} \cdot \mathcal{P}
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- \( \sigma_{tot}(s) \) rather insensitive to pion’s low-energy structure
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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’kov analysis objected by Pasquini, Drechsel, Scherer PRC81, 029802 (2010)
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 $2 \times 10^7$/s  
  (typ. $5 \times 10^6$/s)  
  Nov. 2004, 2008-09, 2012: 
  hadron spec. & Primakoff reactions

- tertiary muons: $4 \times 10^7$/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

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


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

CEDARs

silicon stations

C/Ni/W targets

2009 RPD

SM1

SM2

ECAL1

ECAL2

J. M. Friedrich — Pion Polarisability with COMPASS
Silicon detector module, two-sided $\sigma_{x,y} \sim 5\mu m$
Silicon cryostat in the recoil detector
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.

- 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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- Control systematics by
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  and
  \[ K^- \rightarrow \pi^- \pi^0 \rightarrow \pi \gamma \gamma \]
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

\[ \Delta Q_T \approx 12 \text{ MeV/c} \text{ (190 GeV/c beam requires few-\(\mu\)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?
Coulomb-nuclear interference

Photon density squared form factor

- calculation following G. Fäldt (Phys. Rev. C79, 014607)
- eikonal approximation: pions traverse Coulomb and strong-interaction potentials
Primakoff peak: muon data


COMPASS 2009
\( \mu^- \text{Ni} \rightarrow \mu^- \gamma \text{Ni} \)

- data
- simulation (normalised)

- muon control measurement: pure electromagnetic interaction
Principle of the measurement

- CEDARs
- silicon stations
- 2009 RPD
- C/Ni/W targets
- ECAL1
- SM1
- SM2
- ECAL2
ECAL2: 3000 cells of different types
Figures 3.5 and 3.6: Profile of energy deviations shown for 1/4 of a shashlik block and for muon data photons within the range $133 \text{ GeV} < \gamma < 152 \text{ GeV}$.

from: Th. Nagel, PhD thesis TUM 2012
Photon energy spectra for muon and pion beam


J. M. Friedrich — Pion Polarisability with COMPASS
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:

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

Radiative corrections (Compton scattering part)

Muon Compton scattering: $\mu^- + \gamma \rightarrow \mu^- + \gamma$

Pion Compton scattering: $\pi^- + \gamma \rightarrow \pi^- + \gamma$

$\lambda = 3.8 \text{ MeV}$

$\lambda = 5 \text{ MeV}$


<table>
<thead>
<tr>
<th>source of systematic uncertainty</th>
<th>estimated magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CL = 68 %</td>
</tr>
<tr>
<td></td>
<td>$[10^{-4} \text{ fm}^3]$</td>
</tr>
<tr>
<td>tracking</td>
<td>0.5</td>
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<tr>
<td>radiative corrections</td>
<td>0.3</td>
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<tr>
<td>background subtraction in $Q$</td>
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<tr>
<td>pion electron scattering</td>
<td>0.2</td>
</tr>
<tr>
<td>quadratic sum</td>
<td>0.7</td>
</tr>
</tbody>
</table>
source of systematic uncertainty | estimated magnitude
--- | ---
tracking | 0.5
radiative corrections | 0.3
background subtraction in $Q$ | 0.4
pion electron scattering | 0.2

quadratic sum | 0.7

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 the uncertainties.
About crossing

- red hatched: physical regions
  \[ \gamma + \gamma \rightarrow \pi + \pi \]
  \[ \gamma + \pi \rightarrow \gamma + \pi \]
- two-pion thresholds at \( s = 4m_\pi^2, u = 4m_\pi^2, t = 4m_\pi^2 \)
- DR integration paths
  \[ t = 0 \) (forward), \]
  \[ \theta = 180^\circ \) (backward) \]
  \[ u = m_\pi^2, s = m_\pi^2, \ldots \]
Photon-photon fusion process $\gamma\gamma \rightarrow \pi^+\pi^-$

- Planned measurements at ALICE and JLab

$$
\sigma_{\text{tot}}(s) = \frac{2\pi\alpha^2}{\hat{s}^3 m_\pi^2} \left\{ \left[ 4 + \hat{s} + \hat{s}|C(\hat{s})|^2 \right] \sqrt{\hat{s}(\hat{s} - 4)} + 8 \left[ 2 - \hat{s} + \hat{s}\text{Re}C(\hat{s}) \right] \ln \frac{\sqrt{\hat{s}} + \sqrt{\hat{s} - 4}}{2} \right\},
$$

$$
C(\hat{s}) = -\beta\pi\frac{m_\pi^3}{2\alpha} \hat{s} - \frac{m_\pi^2}{(4\pi f_\pi)^2} \left\{ \frac{\hat{s}}{2} + 2 \left[ \ln \frac{\sqrt{\hat{s}} + \sqrt{\hat{s} - 4}}{2} - \frac{i\pi}{2} \right]^2 \right\},
$$

courtesy Norbert Kaiser (TUM)

Dispersion relations and ChPT

Polarisability and Loop Contributions $z=-1.0$

DR calculations: Barbara Pasquini (Pavia)
Pion polarisability on the lattice

FIGURE 3. Left: electric polarizability for the charged pions as a function of the valence quark mass. The data for $m_\pi = 390$ MeV is taken from [5]. Right: effective mass for a charged pion correlator together with the scalar particle correlator determined from the fit. The fitting range is indicated by the vertical bars.

Alexandru et al., Pion electric polarizability from lattice QCD, arXiv:1501.06516
Pion polarisability measurements at COMPASS

Primakoff pilot run 2004
~1 week
~10k events
0.5X₀ Pb

~63k events
0.3X₀ Ni
~3 weeks

Primakoff run 2009

Primakoff run 2012
~3 months
~200–400k events
0.3X₀ Ni

just seen

Eγ/Ebeam > 0.4
Measurement of the **pion polarisability** at COMPASS

- Via the Primakoff reaction, COMPASS has determined
  
  \[ \alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-4} \text{ fm}^3 \]
  
  assuming \( \alpha_\pi + \beta_\pi = 0 \)

- Most precise experimental determination
- Systematic control: \( \mu \gamma \rightarrow \mu \gamma, \ K^- \rightarrow \pi^- \pi^0 \)

**Chiral dynamics** in \( \pi^- \gamma \rightarrow \pi^- \pi^0 \) and \( \pi \gamma \rightarrow \pi \pi \pi \) reactions

- Charged-channel \( \pi \gamma \rightarrow \pi^- \pi^- \pi^+ \) tree-level ChPT prediction confirmed
- Neutral-channel \( \pi \gamma \rightarrow \pi^- \pi^0 \pi^0 \) analysis ongoing
- Resonance properties, radiative couplings

**High-statistics run 2012**

- separate determination of \( \alpha_\pi \) and \( \beta_\pi \)
- \( s \)-dependent quadrupole polarisabilities
- First measurement of the kaon polarisability
Thanks for your attention!
Access to $\pi + \gamma$ reactions via the Primakoff effect:

At smallest momentum transfers to the nucleus, high-energetic particles scatter predominantly off the electromagnetic field quanta ($\sim Z^2$)

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

**analogously:** Kaon-induced reactions $K^- + \gamma \rightarrow \cdots$
"Low \( t' \)": \( 10^{-3} (\text{GeV}/c)^2 < t' < 10^{-2} (\text{GeV}/c)^2 \) \(~ \sim 2\,000\,000\) events

"Primakoff region": \( t' < 10^{-3} (\text{GeV}/c)^2 \) \(~ \sim 1\,000\,000\) events

2004 Primakoff results

\[ \pi^- \text{Pb} \rightarrow \text{Pb} \pi^- \pi^- \pi^+ \]
ChPT & Resonances in $\pi^- \pi^- \pi^+$

First Measurement of $\pi \gamma \rightarrow 3\pi$ Absolute Cross-Section

Measured absolute cross-section of $\pi^- \gamma \rightarrow \pi^- \pi^- \pi^+$

COMPASS 2004
$
\pi^- \gamma \rightarrow \pi^- \pi^- \pi^+$
from $\pi^- \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \text{Pb}$

- Fitted ChPT Intensity
- Leading Order ChPT Prediction

Full Systematic Error
Luminosity Uncertainty

published in PRL 108 (2012) 192001

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Chiral loops, e.g.
(N. Kaiser, NPA848 (2010) 198)
2004 Primakoff results

\[ \pi^- \text{ Pb} \rightarrow \text{ Pb} \pi^- \pi^- \pi^+ \]

- **"Low }t'":** \(10^{-3} \text{ (GeV/c)}^2 < t' < 10^{-2} \text{ (GeV/c)}^2\) \(\sim 2\,000\,000\) events
- **"Primakoff region":** \(t' < 10^{-3} \text{ (GeV/c)}^2\) \(\sim 1\,000\,000\) events
ChPT & Resonances in $\pi^-\pi^-\pi^+$

2004 Primakoff results

$\pi^-\text{Pb} \rightarrow \text{Pb} \pi^-\pi^-\pi^+$

COMPASS 2004
$\pi\text{Pb} \rightarrow \pi\pi\pi^+\text{Pb}$

PWA of $a_1(1260), a_2(1320)$ contributions in $t$ slices

- "Low $t'$": $10^{-3} (\text{GeV}/c)^2 < t' < 10^{-2} (\text{GeV}/c)^2 \sim 2\,000\,000$ events
- "Primakoff region": $t' < 10^{-3} (\text{GeV}/c)^2 \sim 1\,000\,000$ events
PWA: $a_1$, $a_2$ and $\Delta \Phi$ in separated $t'$ regions

**COMPASS 2004**

$\pi^+\text{Pb} \rightarrow \pi^-\pi^-\pi^+\text{Pb}$

$0.0015 < t' < 0.01 \text{ GeV}^2/c^2$

$t' < 0.0005 \text{ GeV}^2/c^2$

Intensity / (40 MeV/c^2)

Phase (degrees)

$\Delta \Phi (2^{++}1^+ \rho\pi D - 1^{++}0^+ \rho\pi S)$
Radiative Coupling of $a_2(1320)$ and $\pi_2(1670)$

\[ \Gamma_0(a_2(1320) \to \pi\gamma) \, M2 \]

\[ \Gamma_0(\pi_2(1670) \to \pi\gamma) \, E2 \]

\[ \Leftrightarrow \text{meson w.f.'s: } \Gamma_{i \to f} \propto |\langle \Psi_f | e^{-i\vec{q} \cdot \hat{r}} \hat{\epsilon} \cdot \vec{p} |\Psi_i \rangle|^2, \text{ VMD} \]

- normalization via beam kaon decays
- large Coulomb correction

*published in EPJ A50 (2014) 79*
Phase $a_2 - a_1$ in detail: $t'$ dependence

transition of $\pi \gamma$ to $\pi IP \to a_2$ production
work in progress
interference can be used to map details of resonances and production mechanisms
ChPT & Resonances in $\pi^+ \pi^- \pi^+$

**Polarisability effect (LO ChPT values)**

The graph shows the differential cross-section $d\sigma/d\Omega_{\text{cm}}$ as a function of the cosine of the center-of-mass angle $\cos \theta_{\text{cm}}$. The curves are labeled with different values of $s = m^2\pi$, indicating various $s$-values.

- $s = 3m^2\pi$
- $s = 5m^2\pi$
- $s = 8m^2\pi$
- $s = 15m^2\pi$

The graph highlights the Primakoff Primakoff region with $E_\gamma < 20$ GeV.

The expressions
- $\alpha_\pi = 3.00$
- $\beta_\pi = -3.00$

are indicated on the graph.

Loop effects are not shown in the graph.
Polarisability effect (NLO ChPT values)

- - - $\alpha_\pi = 3.00$, $\beta_\pi = -2.86$

loop effects not shown

$E_\gamma < 20$ GeV

$\gamma E^2 \pi s = 3m^2 \pi$

$\gamma E^2 \pi s = 5m^2 \pi$

$\gamma E^2 \pi s = 8m^2 \pi$

$\gamma E^2 \pi s = 15m^2 \pi$

$\cos \theta_{\text{CM}}$

$[\mu b]$
ChPT & Resonances in $\pi^-\pi^-\pi^+$

**Polarisability effect** (wrong sign $\alpha_\pi + \beta_\pi$)

Loop effects not shown

$\frac{d\sigma}{d\Omega_{cm}}$ [\(\mu b\)]

- $s=3m_\pi^2$
- $s=5m_\pi^2$
- $s=8m_\pi^2$
- $s=15m_\pi^2$

$E_\gamma < 20$ GeV

$\alpha_\pi = 3.00$, $\beta_\pi = -3.14$
ChPT & Resonances in $\pi^-\pi^-\pi^+$

Polarisability effect (Serpukhov values)

Loop effects not shown

$\alpha_\pi = 6.10$, $\beta_\pi = -6.10$
Radiative $\pi^+$ production on the proton:

$$\gamma \pi^* \rightarrow \pi \gamma \quad [\text{via } \gamma p \rightarrow n \pi^+ \gamma]$$

Mainz (2005) measurement: $\alpha_{\pi} - \beta_{\pi} = 11.6 \pm 1.5 \pm 3.0 \pm 0.5$

"$\pm 0.5$": model error *only within the used ansatz*,

*full systematics not under control*

Primakoff Compton reaction:

$$\gamma^* \pi \rightarrow \pi \gamma \quad [\text{via } \pi Z \rightarrow Z \pi \gamma]$$

tiny extrapolation $\gamma^* \rightarrow \gamma \mathcal{O}(10^{-3} m_{\pi}^2)$

*fully under theoretical control*

Minimum transverse momentum of the charged particle

\[ p_T \text{ [GeV/c]} \]

Counts / 2.5 MeV/c

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

- **Data**
- **Simulation (normalised)**

J. M. Friedrich — Pion Polarisability with COMPASS
ChPT & Resonances in $\pi^- - \pi^- + \pi^+$

CM energy in $\pi^\gamma \rightarrow \pi^\gamma$

- $\rho$ contribution from $\pi^\gamma \rightarrow \pi\pi^0$
\[ E_{\pi} + E_{\gamma} - E_{\pi} \] vs. \( \sqrt{s} \)

- \( \rho \) contribution from \( \pi \gamma \rightarrow \pi \pi^0 \)

COMPASS 2009
\( \pi \) Ni \( \rightarrow \pi \) \( \gamma \) Ni

preliminary
Mandelstam $\{s,t\} \leftrightarrow$ Laboratory $\{E_\gamma, \theta_\gamma\}$ for $\pi \gamma \rightarrow \pi \gamma$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{ChPT & Resonances in $\pi^- \pi^- \pi^+$}
\end{figure}

J. M. Friedrich — Pion Polarisability with COMPASS
M.R. Pennington in the 2nd DAΦNE Physics Handbook, “What we learn by measuring $\gamma\gamma \to \pi\pi$ at DAΦNE”:

All this means that the only way to measure the pion polarisabilities is in the Compton scattering process near threshold and not in $\gamma\gamma \to \pi\pi$. Though the low energy $\gamma\gamma \to \pi\pi$ scattering is seemingly close to the Compton threshold (...) and so the extrapolation not very far, the dominance of the pion pole (...) means that the energy scale for this continuation is $m_\pi$. Thus the polarisabilities cannot be determined accurately from $\gamma\gamma$ experiments in a model-independent way and must be measured in the Compton scattering region.
Primakoff production of $a_1(1260)$ vs. E272 result

No evidence for $a_1(1260) \rightarrow \pi\gamma$

COMPASS 2004
$\pi\text{Pb} \rightarrow \pi\pi\pi^{+}\text{Pb}$
t' < 0.001 GeV/c²

COMPASS 2004
$\Delta\Phi (\,^{2+}I^+\,\rho\pi\text{D} - \,^{1+}\,I^+\,\rho\pi\text{S})$
t' < 0.001 GeV/c²

COMPASS 2004
$\Delta\Phi (\,^{1+}I^+\,\rho\pi\text{S} - \,^{1+}\,0^+\,\rho\pi\text{S})$

Mass-independent PWA (narrow mass bins):

\[ \sigma_{\text{indep}}(\tau, m, t') = \sum_{\epsilon = \pm 1} \left| \sum_{r=1}^{N_r} T_{ir}^{\epsilon} f_i^{\epsilon}(t') \psi_i^{\epsilon}(\tau, m) \right| \sqrt{\int |f_i^{\epsilon}(t')|^2 dt'} \sqrt{\int |\psi_i^{\epsilon}(\tau', m)|^2 d\tau'} \]

- Production strenght assumed constant in single bins
- Decay amplitudes \( \psi_i^{\epsilon}(\tau, m) \), with \( t' \) dependence \( f_i^{\epsilon}(t') \)
- Production amplitudes \( T_{ir}^{\epsilon} \rightarrow \) Extended log-likelihood fit
- Acceptance corrections included

Spin-density matrix: \( \rho_{ij}^{\epsilon} = \sum_r T_{ir}^{\epsilon} T_{jr}^{\epsilon*} \)

→ Physical parameters:

\[ \text{Intens}_i^{\epsilon} = \rho_{ii}^{\epsilon}, \]
\[ \text{relative phase} \Phi_{ij}^{\epsilon} \]
\[ \text{Coh}_{i,j}^{\epsilon} = \sqrt{\left( \Re \rho_{ij}^{\epsilon} \right)^2 + \left( \Im \rho_{ij}^{\epsilon} \right)^2} / \sqrt{\rho_{ii}^{\epsilon}\rho_{jj}^{\epsilon}} \]

Mass-dependent \( \chi^2 \)-fit (not presented here):

- \( X \) parameterized by Breit-Wigner (BW) functions
- Background can be added
ChPT & Resonances in $\pi^- \pi^- \pi^+$

Mass dependence of the diffractive slope

![Graph showing the mass dependence of the diffractive slope](graph.png)

COMPASS 2004

$\pi^- \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \text{Pb}$

Diffractive slope $b_{\text{diff}}$ vs. Mass of $\pi^- \pi^- \pi^+$ system (GeV/c$^2$)

J. M. Friedrich — Pion Polarisability with COMPASS
**Partial Wave Analysis Formalism**

**Isobar Model**

- **Isobar model:** Intermediate 2-particle decays
- **Partial wave in reflectivity basis:** \( J^{PC} M^\epsilon [isobar] L \)

- **Mass-independent PWA** (40 MeV/\( c^2 \) mass bins): 38 waves
  - Fit of angular dependence of partial waves, interferences
- **Mass-dependent \( \chi^2 \)-fit** (Not presented here)

**Diagram:**

- **\( \pi^- \)(beam)**
- **\( \pi^- \)(bachelor)**
- **\( \pi^- \)**
- **\( \pi^+ \)**
- **Target**
- **Recoil**

**Parity Exchange:**

- \( \epsilon = + \): natural parity exchange
- \( \epsilon = - \): unnatural parity exchange

**Mass-dependent \( \chi^2 \)-fit** (Not presented here)
Major intensities in $m(3\pi)$-bins (acceptance corrected)

$\pi^+\pi^-\pi^-$ System (GeV/c)$^2$

$M=0$ Spin Total

$M=1$ Spin Total

$A_2(1320)$

$A_1(1260)$

$1^{++}0^{+} \rho \pi S$

$2^{++}1$ Spin Total

COMPASS 2004

$\pi^+\pi^-\pi^+\pi^0\pi^+$ Pb
$t' < 0.001$ GeV$^2$/c$^2$

PRELIMINARY
ChPT & Resonances in $\pi^+\pi^-\pi^+$

PWA of data with low $t'$

Intensity of selected waves: $0^{-+}0^+ f_0(980)\pi S$, $1^{++}0^+ \rho \pi S$, $2^{++}1^+ \rho \pi D$, $2^{-+}0^+ f_2(1270)\pi S$

COMPASS 2004
$\pi^-\text{Pb} \rightarrow \pi\pi^+\text{Pb}$
$0.001 < t' < 0.01$ GeV$^2$/c$^2$

Intensity / (40 MeV/c$^2$)

COMPASS 2004
$\pi^-\text{Pb} \rightarrow \pi\pi^+\text{Pb}$
$0.001 < t' < 0.01$ GeV$^2$/c$^2$

Intensity / (40 MeV/c$^2$)

COMPASS 2004
$\pi^-\text{Pb} \rightarrow \pi\pi^+\text{Pb}$
$0.001 < t' < 0.01$ GeV$^2$/c$^2$

Intensity / (40 MeV/c$^2$)
"Spin Totals": Sum of all contributions for given M (i.e. $z$-projection of J)

$t'$-dependent amplitudes:

Primakoff production: $\mathbf{M=1}: \sigma(t') \propto e^{-b_{\text{Prim}}t'} \rightarrow$ arises at $t' \approx 0$ (resolved shape!)

Diffractive production: $\mathbf{M=0}: \sigma(t') \propto e^{-b_{\text{diff}}(m)t'}$

$\mathbf{M=1}: \sigma(t') \propto t' e^{-b_{\text{diff}}(m)t'} \rightarrow$ vanishes for $t' \approx 0$
ChPT & Resonances in $\pi^-\pi^-\pi^+$

**Theory: Phase $a_2$ (strong+Coulomb) - $a_1$ (strong)**

**ChPT & Resonances in $\pi^-\pi^-\pi^+$**

**Theory: Phase $a_2$ (strong+Coulomb) - $a_1$ (strong)**

**Glauber modell**


Plot: N. Kaiser (TU München)

⇒ indicates confirmation of interference Coulomb-interaction - strong interaction
⇒ detailed studies of the nature of resonances

**COMPASS 2004**

$\pi^-\text{Pb} \rightarrow \pi^-\pi^-\pi^+\text{Pb}$

$t' < 0.02 \text{ GeV}^2/c^2$

$1.26 < m_{\pi\pi} < 1.38 \text{ GeV}/c^2$

**Glauber modell**


Plot: N. Kaiser (TU München)

⇒ indicates confirmation of interference Coulomb-interaction - strong interaction
⇒ detailed studies of the nature of resonances
Primakoff contribution at $t' < 10^{-3} \text{ (GeV/c)}^2$

Primakoff: $\sigma(t') \propto e^{-b_{\text{Prim}}t'}$, $b_{\text{Prim}} \approx 2000 \text{ (GeV/c)}^{-2}$ (mainly resolution)

Diffractive: $\sigma(t') \propto e^{-b_{\text{diff}}t'}$, $b_{\text{diff}} \approx 400 \text{ (GeV/c)}^{-2}$ for lead target

(Mass) spectrum of this Primakoff contribution?

⇒ Statistical subtraction of diffractive background (for bins of $m_{3\pi}$)