Photons Interacting with Pions at COMPASS

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COMPASS collaboration

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COMpass Pion polarisability and Resonances in $\pi^- \pi^- \pi^+$.

**Summary and Outlook**

**Common 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
Physics fields at COMPASS

- lepton scattering at high momentum transfer → partonic structure of the nucleons

- diffractive dissociation of pions and kaons → meson spectrometry

- scattering of pions (and kaons) in nuclear Coulomb field → low-energetic meson-photon reactions
  \( \pi \gamma \rightarrow \pi \gamma \) (pion polarisability), \( \pi \gamma \rightarrow 3\pi \) (chiral dynamics, radiative couplings)
Physics fields at COMPASS

- lepton scattering at high momentum transfer → partonic structure of the nucleons
  *s. talk tomorrow by A. Ferrero*

- diffractive dissociation of pions and kaons → meson spectrometry
  *s. following talk by B. Grube*

- scattering of pions (and kaons) in nuclear Coulomb field → low-energetic meson-photon reactions *(this talk)*
  \[ \pi \gamma \rightarrow \pi \gamma \] (pion polarisability), \[ \pi \gamma \rightarrow 3\pi \] (chiral dynamics, radiative couplings)
Fixed-target experiment

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

![Diagram of the experimental setup]

ECAL1
HCAL1
SM2
Si Telescope
RICH1
Target RPD
SM1
Muon Filter 1
Muon Filter 2
ECAL2
HCAL2
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
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 $\approx 1 \text{Å}^3$]

- Theory: ChPT (2-loop) prediction:
  \[
  \begin{align*}
  \alpha_\pi - \beta_\pi & = 5.7 \pm 1.0 \\
  \alpha_\pi + \beta_\pi & = 0.16 \pm 0.1
  \end{align*}
  \]

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

  ($\alpha_\pi + \beta_\pi = 0$ assumed)
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 $\approx 1 \, \text{Å}^3$]

Theory: ChPT (2-loop) prediction:

- $\alpha_\pi = 2.93 \pm 0.5$
- $\beta_\pi = -2.77 \pm 0.5$

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

$(\alpha_\pi + \beta_\pi = 0$ assumed)
Measurement of the Charged-Pion Polarizability

C. Adolph, R. Akhunzyanov, 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
Principle of the COMPASS measurement

- high-energetic pion beam on 4mm nickel disk
- observe scattered pions in coincidence with produced hard photons
- study of cross-section shape
Polarisability effect in Primakoff technique

- 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

- Charged pions traverse the nuclear electric field
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  - Compton cross-section typically diminished
  - corresponding charge separation $\approx 10^{-5} \text{ fm} \cdot e$
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)
**Pion Compton Scattering**

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

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

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

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

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

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\]

\[
z_\pm = 1 \pm \cos \theta_{cm}
\]
Principle of the measurement
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
  \[ K^- \rightarrow \pi^-\pi^0 \rightarrow \pi\gamma\gamma \]
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
  
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- **Control systematics by**
  
  \[ \mu \gamma \{ \text{Ni} \rightarrow \text{Ni}' \} \rightarrow \mu \gamma \]

  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%)
- ~ 63,000 exclusive events ($x_\gamma > 0.4$) (Serpukhov ~ 7000 for $x_\gamma > 0.5$)
Primakoff peak


- \[ \Delta Q_T \approx 12 \text{ MeV/c} \] (190 GeV/c beam \( \rightarrow \) 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?
Primakoff peak: muon data


[Graph showing counts per 2.74 MeV/c vs. |Q| [GeV/c]]

- muon control measurement: pure electromagnetic interaction
- e.m. nuclear effects well understood
Principle of the measurement

CEDARs

silicon stations

2009 RPD

C/Ni/W targets

ECAL1

SM1

SM2

ECAL2

C/Ni/W targets

2009 RPD

silicon stations

CEDARs
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
Photon energy spectra for muon and pion beam


\[ f_{T_\gamma} [\%] \]
\[ x_\gamma \]

\[ \text{counts / 0.025} \]
\[ 0.4 \ 0.5 \ 0.6 \ 0.7 \ 0.8 \ 0.9 \]

\[ \mu^- \text{ data x2} \]
\[ \mu^- \text{ simulation} \]

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

\[ \lambda = 3.8 \text{ MeV} \]

\[ \lambda = 5 \text{ MeV} \]


<table>
<thead>
<tr>
<th>source of systematic uncertainty</th>
<th>estimated magnitude</th>
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</thead>
<tbody>
<tr>
<td>determination of tracking-detector efficiencies</td>
<td>0.5</td>
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<tr>
<td>treatment of radiative corrections</td>
<td>0.3</td>
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<tr>
<td>subtraction of $\pi^0$ background</td>
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<tr>
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---|---
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pion-electron elastic scattering | 0.2

contribution of muons in the beam | 0.05

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.
**Photon-photon fusion process** $\gamma \gamma \rightarrow \pi^+ \pi^-$

- Planned measurements at ALICE and JLab

\begin{align*}
\sigma_{tot}(s) &= \frac{2\pi\alpha^2}{\hat{s}^3 m^2_\pi} \left\{ [4 + \hat{s} + \hat{s}|C(\hat{s})|^2] \sqrt{\hat{s}(\hat{s} - 4)} \\
&\quad + 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^3_\pi}{2\alpha} \hat{s} - \frac{m^2_\pi}{(4\pi f_\pi)^2} \left\{ \hat{s} \frac{\hat{s}}{2} + 2 \left[ \ln \frac{\sqrt{\hat{s} + \sqrt{\hat{s} - 4}}}{2} - \frac{i\pi}{2} \right]^2 \right\}
\end{align*}

![Graph](image)

*courtesy Norbert Kaiser (TUM)*

limited sensitivity to the polarisability contribution
Polarisability and Loop Contributions $z=-1.0$

![Graph showing dispersion relations and ChPT calculations](image)

- **LEX** $\alpha=-\beta=2.00$
- **LEX** $\alpha=-\beta=2.85$
- **LEX** ($\alpha=0$) + chiral loops
- **LEX** ($\alpha=2$) + chiral loops

**DR calculations: Barbara Pasquini (Pavia)**

$\sigma/\sigma_{\text{Born}}$ vs. $\sqrt{s/m_\pi}$

- Chiral loops, $\alpha=0.00$
- $\beta=-\alpha_{\text{LEX}}$
- $\beta=2.85$
- $\beta=2.00$
- Dispersion relations and ChPT
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
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 ($\sim Z^2$)

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

analogously: Kaon-induced reactions $K^- + \gamma \rightarrow \cdots$
2004 Primakoff results

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

- "Low \( t' \)":
  \[ 10^{-3} \text{ (GeV/c)}^2 < t' < 10^{-2} \text{ (GeV/c)}^2 \]
  \( \sim 2 \times 10^6 \) events

- "Primakoff region":
  \[ t' < 10^{-3} \text{ (GeV/c)}^2 \]
  \( \sim 1 \times 10^6 \) events
Chiral dynamics in $\pi \gamma \rightarrow 3\pi$

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

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

$\Gamma_0(a_2(1320) \rightarrow \pi\gamma) = M2$

$\Gamma_0(\pi_2(1670) \rightarrow \pi\gamma) = E2$

$\Leftrightarrow$ meson w.f.'s: $\Gamma_{i \rightarrow f} \propto |\langle \psi_f | e^{-i\vec{q} \cdot \vec{r}} \hat{\epsilon} \cdot \vec{p} | \psi_i \rangle |^2$, VMD

- normalization via beam kaon decays
- large Coulomb correction

published in EPJ A50 (2014) 79
Summary and Outlook

- Measurement of the pion polarisability at COMPASS
  - Via the Primakoff reaction, COMPASS has determined
    \[ \alpha_\pi = \left( 2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{syst}} \right) \times 10^{-4} \text{fm}^3 \]
    assuming \( \alpha_\pi + \beta_\pi = 0 \)
  - Most direct access to the \( \pi \gamma \to \pi \gamma \) process
  - Most precise experimental determination
  - Systematic control: \( \mu \gamma \to \mu \gamma, K^- \to \pi^- \pi^0 \)

- COMPASS measures more aspects of chiral dynamics in \( \pi^- \gamma \to \pi^- \pi^0 \) and \( \pi \gamma \to \pi \pi \pi \) reactions

- High-statistics run 2012
  - Separate determination of \( \alpha_\pi \) and \( \beta_\pi \)
  - \( s \)-dependent quadrupole polarisabilities
  - First measurement of the kaon polarisability
Thank you for your attention!
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
About crossing

- red hatched: physical regions
  \( \gamma + \gamma \rightarrow \pi + \pi \)
  \( \gamma + \pi \rightarrow \gamma + \pi \)

- two-pion thresholds
  at \( s = 4m^2_\pi, u = 4m^2_\pi \),
  \( t = 4m^2_\pi \)

- DR integration paths
  \( t = 0 \) (forward),
  \( \theta = 180^\circ \) (backward)
  \( u = m^2_\pi, s = m^2_\pi, \ldots \)

from: D. Drechsel, talk at IWHSS 2011 Paris
Pion polarisability measurements at COMPASS

- Primakoff pilot run 2004
  - ~63k events
  - 0.3X₀ Ni
  - ~3 weeks

- Primakoff run 2009
  - ~3 months
  - ~200–400k events
  - 0.3X₀ Ni
  - just seen

- Primakoff run 2012
  - ~1 week
  - ~10k events
  - 0.5X₀ Pb

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

\[ z_{\pm} = 1 \pm \cos \theta_{cm} \]
Polarisability effect (LO ChPT values)

\[
\theta_{\text{CM}} \cos^{-1} \left[ \frac{\theta_{\text{CM}} \cos \theta_{\text{CM}}}{\sigma_d} \right] = \begin{cases} 
0.02 & \text{if } d \geq 20 \text{ GeV} \\
0.1 & \text{if } d < 20 \text{ GeV} 
\end{cases}
\]

\[
\gamma_E = \frac{s}{2m_\pi^2}
\]

\[
\beta_\pi = 3.00, \quad \alpha_\pi = -3.00
\]
Polarisability effect (NLO ChPT values)

Loop effects not shown

\[ \frac{d\sigma}{d\Omega_{\text{cm}}} \text{ [\mu b]} \]

\[ s = 3m_{\pi}^2 \]
\[ s = 5m_{\pi}^2 \]
\[ s = 8m_{\pi}^2 \]
\[ s = 15m_{\pi}^2 \]

\[ \beta_{\pi} = -2.86 \]

\[ \alpha_{\pi} = 3.00 \]

\[ E_{\gamma} < 20 \text{ GeV} \]
Polarisability effect with “wrong-sign” $\alpha_\pi + \beta_\pi < 0$

$\alpha_\pi = 3.00, \beta_\pi = -3.14$

Loop effects not shown.
Polarisability effect (Serpukhov values)

\[ d\sigma / d\Omega_{\text{cm}} \]  
\[ \theta \cos^{-1} \]
\[ -0.8 \quad -0.6 \quad -0.4 \quad -0.2 \quad 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \]

\[ \mu \]  
\[ \Omega / d\sigma d \]
\[ 0.02 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \]
\[ < 20 \text{ GeV} \]

Primakoff \[ \gamma \]
\[ 2 \pi \]
\[ s=3m^2 \]
\[ s=5m^2 \]
\[ s=8m^2 \]
\[ s=15m^2 \]

\[ \alpha_\pi = 6.10, \beta_\pi = -6.10 \]

loop effects not shown
Radiative $\pi^+$ production on the proton:

$$\gamma \pi^* \rightarrow \pi \gamma$$  \hspace{1cm} [via $\gamma p \rightarrow n \pi^+ \gamma$]

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

“±0.5”: model error only within the used ansatz, full systematics not under control

Primakoff Compton reaction:

$$\gamma^* \pi \rightarrow \pi \gamma$$  \hspace{1cm} [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

\[ p_T \] [GeV/c]

counts / 2.5 MeV/c

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

data

simulation (normalised)
CM energy in $\pi \gamma \rightarrow \pi \gamma$

- $\rho$ contribution from $\pi \gamma \rightarrow \pi \pi^0$
Exclusivity vs. $\sqrt{s}$

COMPASS 2009

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

$E_{\pi^+} + E_{\gamma} - E_{\pi^-}$

$m_{\pi\gamma}$ [GeV/$c^2$]

$E'_{\pi^-}$

$\rho$ contribution from $\pi\gamma \rightarrow \pi\pi^0$
Mandelstam \( \{s,t\} \leftrightarrow \) Laboratory \( \{E_\gamma, \theta_\gamma\} \)

for \( \pi \gamma \rightarrow \pi \gamma \)
Cross section graph showing the distribution of cross section as a function of $\sqrt{s}/m_{\pi}$ and $\cos \theta_{CM}$.
M.R. Pennington in the 2\textsuperscript{nd} DA\\Phi\textsc{ne} Physics Handbook, “What we learn by measuring $\gamma\gamma \rightarrow \pi\pi$ at DA\\Phi\textsc{NE}”: All this means that the only way to measure the pion polarisabilities is in the Compton scattering process near threshold and not in $\gamma\gamma \rightarrow \pi\pi$. Though the low energy $\gamma\gamma \rightarrow \pi\pi$ scattering is seemingly close to the Compton threshold (...) and so the \textit{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.
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
2004 Primakoff results

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

PWA of a$_1$(1260), a$_2$(1320) contributions in t slices

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

COMPASS 2004
$\pi \text{Pb} \rightarrow \pi \pi \pi^+\text{Pb}$
$0.0015 < t' < 0.01 \text{ GeV}^2/c^2$
$t' < 0.0005 \text{ GeV}^2/c^2$

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

$\times 10^3$

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

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

$\times 10^3$

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

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

$\Delta \Phi (2^{++}1^+ \rho \pi D - 1^{++}0^+ \rho \pi S )$

COMPASS 2004
$\pi \text{Pb} \rightarrow \pi \pi \pi^+\text{Pb}$
$0.0015 < t' < 0.01 \text{ GeV}^2/c^2$
$t' < 0.0005 \text{ GeV}^2/c^2$
Phase $a_2 - a_1$ in detail: $t'$ dependence

- transition of $\pi\gamma$ to $\pi IP \rightarrow a_2$ production
- work in progress
- interference can be used to map details of resonances and production mechanisms

COMPASS 2004

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

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

$1.26 < m_{3\pi} < 1.38 \text{ GeV}/c^2$
Primakoff production of $a_1(1260)$ vs. E272 result

No evidence for $a_1(1260) \rightarrow \pi\gamma$
**Mass-independent** PWA (narrow mass bins):

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

- Production strength 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:**

$$\rho_{ij}^\epsilon = \sum_r T_{ir}^\epsilon T_{jr}^\epsilon^*$$

$\rightarrow$ Physical parameters:

- Intens$^\epsilon_i = \rho_{ii}^\epsilon$,
- relative phase $\Phi_{ij}^\epsilon$
- Coh$^\epsilon_{i,j} = \sqrt{\left( \text{Re} \rho_{ij}^\epsilon \right)^2 + \left( \text{Im} \rho_{ij}^\epsilon \right)^2} \sqrt{\rho_{ii}^\epsilon \rho_{jj}^\epsilon}$

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

- $X$ parameterized by Breit-Wigner (BW) functions
- Background can be added
Mass dependence of the diffractive slope

COMPASS 2004

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

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

Preliminary
Partial Wave Analysis Formalism

Isobar Model

- Isobar model: Intermediate 2-particle decays
- Partial wave in reflectivity basis: $J^{PC} M^\varepsilon [\text{isobar}] L$

- 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)
Major intensities in \(m(3\pi)\)-bins (acceptance corrected)

\[
\begin{align*}
\text{COMPASS 2004} & \quad \pi\text{Pb} \rightarrow \pi\pi\pi^+\text{Pb} \\
&t' < 0.001 \text{ GeV}^2\text{c}^2 \\
\end{align*}
\]

- **M=0 Spin Total**
- **M=1 Spin Total**
- \(a_1(1260)\)
  - \(1^{++}\) \(\rho\pi\) \(S\)
- \(a_2(1320)\)

\[
\begin{align*}
\text{COMPASS 2004} & \quad \pi\text{Pb} \rightarrow \pi\pi\pi^+\text{Pb} \\
&t' < 0.001 \text{ GeV}^2\text{c}^2 \\
\end{align*}
\]
PWA of data with low $t'$

Intensity of selected waves: $0^{-+}0^+ f_0(980)\pi S$, $1^{++}0^+ \rho \pi S$, $2^{++}1^+ \rho \pi D$, $2^{-+}0^+ f_2(1270)\pi S$
"Spin Totals": Sum of all contributions for given M (i.e. z-projection of J)

$t'$-dependent amplitudes:

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

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

\( M=1: \sigma(t') \propto t' e^{-b_{\text{diff}}(m)t'} \rightarrow \text{vanishes for } t' \approx 0 \)
**Theory: Phase** \(a_2\text{(strong+Coulomb)}-a_1\text{(strong)}\)

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 $m_{3\pi}$)
Higher-order effects

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

$\sigma_{\text{tot}}$ [
µb]

$\text{total cross section: } \pi \gamma \rightarrow \pi^+ \pi^- \pi^0$

$\text{total cross section: } \pi \gamma \rightarrow \pi^+ \pi^- \pi^-$

$\text{tree approximation}$

$\text{with chiral loops+cts}$

$\text{tree approx. } m_\pi < m_{\rho}$

$\rho$ terms:
First Measurement of $\pi \gamma \to 3\pi$ Absolute Cross-Section

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

COMPASS 2004

$\pi^- \gamma \to \pi^- \pi^- \pi^+$
from $\pi^- \text{Pb} \to \pi^- \pi^- \pi^+ \text{Pb}$

- Fitted ChPT Intensity
- Leading Order ChPT Prediction

Full Systematic Error
Luminosity Uncertainty

published in PRL 108 (2012) 192001
Partial Wave Analysis

*Isobaric Model – Chiral Wave*

\[ \pi^- \gamma \rightarrow \pi^- \pi^0 \pi^0 \]

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Partial Wave Analysis

Chiral Model - Amplitudes

\[ \pi^- \gamma \rightarrow \pi^- \pi^0 \pi^0 \]

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