The charged-pion polarisability
and more measurements on chiral dynamics
at COMPASS

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COMPASS collaboration

The 8th International Workshop
on Chiral Dynamics, Pisa

1. July 2015
Introduction  COMPASS  Pion polarisability  ChPT & Resonances in $\pi^+ \pi^- \pi^+$  Summary and Outlook

**Pion polarisability and theoretical expectation**

- **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 $\approx 1$ A$^3$]

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


- Relevant low-energy constants from the measurement of $\pi^+ \to e^+ \nu_e \gamma$

Pion polarisability and theoretical expectation

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Theory: ChPT (2-loop) prediction:

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


Relevant low-energy constants from the measurement of $\pi^+ \rightarrow e^+ \nu_e \gamma$

Recent precision measurements: PIBETA PRL93(2004)181804, update (and wangled “$\alpha_{\pi} = -\beta_{\pi}$” value) in PRL103(2009)051802
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\end{align*}
\]


relevant low-energy constants from the measurement of $\pi^+ \rightarrow e^+ \nu_e \gamma$


experimental value?
Pion Compton Scattering

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

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

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

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

\[
z_\pm = 1 \pm \cos \theta_{cm}
\]
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’kiov analysis objected by Pasquini, Drechsel, Scherer PRC81, 029802 (2010)
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 $\approx 10^{-5} \text{fm} \cdot e$
Charged pions traverse the nuclear electric field
- typical field strength at $d = 5R_{Ni}$:

$$E \approx 300 \text{ kV/fm}$$

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pion/muon (quasi-)real
Compton scattering
Polarisability contribution
Compton cross-section typically diminished
respective charge separation $\approx 10^{-5} \text{ fm} \cdot e$

details: see later

photon exchange
strong interaction
typically diminished

$\begin{array}{c|c|c|c|c|c|c}
 Tq0 & 0.05 & 0.1 & 0.15 & 0.2 & 0.25 & 0.5 & 1 & 1.5 & 2 & 2.5 & 3 \\
 \hline
 0 &  &  &  &  &  &  & & \\
 0.5 &  &  &  &  &  &  & & \\
 1 &  &  &  &  &  &  & & \\
 1.5 &  &  &  &  &  &  & & \\
 2 &  &  &  &  &  &  & & \\
 2.5 &  &  &  &  &  &  & & \\
 3 &  &  &  &  &  &  & & \\
\end{array}$

J. M. Friedrich — Chiral Dynamics with COMPASS
CERN SPS: protons $\sim 400$ GeV

- secondary $\pi, K, (\bar{\rho})$: up to $2 \cdot 10^7$/s (typ. $5 \cdot 10^6$/s)
  Nov. 2004, 2008-09, 2012:
  hadron spec. & Primakoff reactions
- 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

- 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 COMPASS measurement

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

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- Control systematics by
  \[ \mu \gamma \{Ni \rightarrow Ni'\} \rightarrow \mu \gamma \]
  and
  \[ K^- \rightarrow \pi^- \pi^0 \rightarrow \pi \gamma \gamma \]
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 \( \pi^- \mathrm{Ni} \rightarrow \pi^- \gamma \mathrm{Ni} \), 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, \( Q^2 < 0.0015 \text{ (GeV}/\text{c})^2 \). From a sample of 63,000 events, the pion electric polarizability is determined to be \( \alpha_x = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{sys}}) \times 10^{-4} \text{ fm}^3 \) 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

\[ \Delta Q_T \approx 12 \text{ MeV/c} \] (190 GeV/c beam \( \to \) 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 \( \to \) negative interference?
Coulomb-nuclear interference

Photon density squared form factor

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


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

Counts / 0.025

$\mu^-$ data x2
$\mu^-$ simulation

$\pi^-$ data
$\pi^-$ simulation

$f_{T \pi}$ [%]

$0.4 \ 0.5 \ 0.6 \ 0.7 \ 0.8 \ 0.9$

$X_{\gamma}$

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

(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)

implemented on the level of the COMPASS Monte Carlo simulation, including soft photon emission

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

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

muon Compton scattering: \( \mu^- + \gamma \rightarrow \mu^- + \gamma \)

pion Compton scattering: \( \pi^- + \gamma \rightarrow \pi^- + \gamma \)


### COMPASS Pion polarisability

#### ChPT & Resonances in $\pi^− \pi^- \pi^+$

#### Summary and Outlook

The COMPASS result for the pion polarisability is given by:

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

The estimated magnitude with a confidence level (CL) of 68% is $10^{-4} \text{fm}^3$.

<table>
<thead>
<tr>
<th>Source of Systematic Uncertainty</th>
<th>Estimated Magnitude</th>
</tr>
</thead>
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<tr>
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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 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)
  \( u = m_{\pi}^2, s = m_{\pi}^2, \ldots \)

from: D. Drechsel, talk at IWHSS 2011 Paris
Photon-photon fusion process $\gamma\gamma \rightarrow \pi^+\pi^-$

- Planned measurements at ALICE and JLab

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

![Graph of total cross section $\sigma_{\text{tot}}(s)$](courtesy Norbert Kaiser (TUM))
Polarisability, loop contributions, dispersion relations

\[
\frac{\sigma}{\sigma_{\text{Born}}} \quad \cos(\theta_{\text{CM}}) = -1.0
\]

\begin{align*}
\alpha = -\beta & = 2.00 \\
\alpha = -\beta & = 2.85
\end{align*}
Polarisability, loop contributions, dispersion relations

\[
\frac{\sigma}{\sigma_{\text{Born}}} = 1.05 \\
\cos(\theta_{\text{CM}}) = -1.0
\]

- **Chiral loops, \(\alpha = 0.00\)**
- **LEX \(\alpha = -\beta = 2.00\)**
- **LEX \(\alpha = -\beta = 2.85\)**
Polarisability, loop contributions, dispersion relations

\[ \text{Polarisability, loop contributions, dispersion relations} \]

\[ \frac{\sigma}{\sigma_{\text{Born}}} \]

- **LEX** $\alpha = -\beta = 2.00$
- **LEX** $\alpha = -\beta = 2.85$
- **LEX + chiral loops**
- **DR [B. Pasquini]**

\[ \cos(\theta_{\text{CM}}) = -1.0 \]
Polarisability, loop contributions, dispersion relations

\[ \frac{\sigma}{\sigma_{\text{Born}}} \]

- **LEX**  \( \alpha = \beta = 2.00 \)
- **LEX**  \( \alpha = \beta = 2.85 \)
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\[ \cos(\theta_{\text{CM}}) = -1.0 \]
Polarisability, loop contributions, dispersion relations

\[ \cos(\theta_{\text{CM}}) = -1.0 \]

\[ \sigma / \sigma_{\text{Born}} \]

- \( \alpha = -\beta = 2.00 \)
- \( \alpha = -\beta = 2.85 \)
- LEX + chiral loops
- DR [B. Pasquini]

\[ \sqrt{s/m} = 2.7 \]

chiral loops, \( \alpha = 0.00 \)

\[ \theta = \cos^{-1}(\cos(\theta_{\text{CM}})) = 2.7 \pi / m \]

\[ \sigma_{\text{LEX}}(\alpha = 2.00) + \text{chiral loops} \]
\[ \sigma_{\text{LEX}}(\alpha = 0.00) + \text{chiral loops} \]
Polarisability, loop contributions, dispersion relations

\[ \frac{\sigma}{\sigma_{\text{Born}}} \]

\[ \cos(\theta_{\text{CM}}) = -1.0 \]

- LEX $\alpha = \beta = 2.00$
- LEX $\alpha = -\beta = 2.85$
- LEX $\alpha = -\beta = 6.80$

chiral loops, $\alpha = 0.00$

$\sqrt{s}/m_\pi = 2.7$
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
0.3X_0 Ni

~63k events
E_\gamma/E_{beam} > 0.4
0.3X_0 Ni
~3 weeks
Primakoff run 2009

~1 week
~10k events
0.5X_0 Pb

~3 months
~200–400k events
0.3X_0 Ni
just seen

Primakoff run 2012

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

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

\[ \frac{d\sigma}{d\Omega_{\text{cm}}} \]
Polarisability effect (NLO ChPT values)

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

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

\[ \cos \theta_{\text{cm}} \]

\[ \alpha_\pi = 3.00, \beta_\pi = -2.86 \]

loop effects not shown

\[ E_\gamma < 20 \text{ GeV} \]
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)

\[ d\sigma / d\Omega_{\text{cm}} \] (0.02, 0.1, 0.2, 0.3, 0.4)

\( s = 3m_\pi^2 \)

\( s = 5m_\pi^2 \)

\( s = 8m_\pi^2 \)

\( s = 15m_\pi^2 \)

\(- - - \alpha_\pi = 6.10, \beta_\pi = -6.10\)

Loop effects not shown

\( E_\gamma < 20 \text{ GeV} \)
Primakoff reactions accessible at COMPASS

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

chiral anomaly, delayed

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

analogous: \textit{Kaon-induced reactions} \( K^- + \gamma \rightarrow \ldots \)
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
Chiral dynamics in $\pi \gamma \rightarrow 3\pi$

**Summary and Outlook**

Total cross section: $\pi \gamma \rightarrow \pi^+ \pi^- \pi^+$

```
\sigma_{tot} [\mu b]
```

Tree approximation with chiral loops + cts

Luminosity Uncertainty

Fitted ChPT Intensity

Normalisation: analysis ongoing

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

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

- Radiative width for $a_2(1320)$: $358 \pm 6 \pm 42$ keV, larger than PDG value ($287 \pm 30$ keV)
- First measurement for $\pi_2(1670)$

*published in EPJ A50 (2014) 79*
Measurement of the pion polarisability at COMPASS

- Via the Primakoff reaction, COMPASS has determined

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

assuming \( \alpha_\pi + \beta_\pi = 0 \)

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

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

High-statistics run 2012

- separate determination of \( \alpha_\pi \) and \( \beta_\pi \)
- \( s \)-dependent quadrupole polarisabilities
- First measurement of the kaon polarisability
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

$\sigma_\gamma$ [µb]

$0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2$

$m_{3\pi}$ [GeV/c$^2$]

$0.45 \quad 0.5 \quad 0.55 \quad 0.6 \quad 0.65 \quad 0.7$

published in PRL 108 (2012) 192001
Higher-order effects

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

ρ terms:
Partial Wave Analysis

*Isobaric Model – Chiral Wave*

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

J. M. Friedrich — Chiral Dynamics with COMPASS

*PRELIMINARY*
Partial Wave Analysis

Chiral Model - Amplitudes

π^- γ → π^- π^0 π^0

π^- Ni → π^- π^0 π^0 (COMPASS 2009)
Ampl(χPT)_{ρρ}

π^- Ni → π^- π^0 π^0 (COMPASS 2009)
Ampl(χPT)_{ρρ}

PRELIMINARY
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
"Low $t'$": $10^{-3} \text{(GeV/c)}^2 < t' < 10^{-2} \text{(GeV/c)}^2 \sim 2000000 \text{ events}$

"Primakoff region": $t' < 10^{-3} \text{(GeV/c)}^2 \sim 1000000 \text{ events}$
PWA: $a_1$, $a_2$ and $\Delta \Phi$ in separated $t'$ regions

COMPASS 2004

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

0.0015 $<$ $t'$ $<$ 0.01 GeV/$c^2$

t' $<$ 0.0005 GeV/$c^2$

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

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

Phase (degrees)

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

2$^+$1$^+$ $\rho \pi D$

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

COMPASS 2004

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

0.0015 $<$ $t'$ $<$ 0.01 GeV/$c^2$

t' $<$ 0.0005 GeV/$c^2$

Mass of $\pi^- \pi^+ \pi^-$ System (GeV/$c^2$)
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
Radiative $\pi^+$ production on the proton:

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

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:

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

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

fully under theoretical control

DR vs. chiral loops

Pion Compton scattering cross-section at $m_{\pi} = 2.7m_{n}$

Relative effect of pion polarisability + loops/DR
tially to our $\pi e^{2\gamma}$ data set. Our best-fit value of $F_A$ agrees well with ChPT calculations, tending to the top of the reported range [7–9]. However, a more precise measurement of $\tau_{\pi^0}$ is needed in order that the sensitivity of our data, expressed in Eq. (2), be put to full use in determining $F_A$. We use our form factor results to evaluate the pion polarizability $\alpha_E$ and the ChPT parameter sum $L_9^r + L_{10}^r$ at leading order as follows: Using the one-parameter fit, we obtain $\alpha_E = -\beta_M = 2.78(2)_{\text{expt}}(10)_{F_V} \times 10^{-4}$ fm$^3$, and $L_9^r + L_{10}^r = 0.00145(1)_{\text{expt}}(5)_{F_V}$, where the first uncertainty comes from the fit and the second from the current CVC-derived value of $F_V$. Alternatively, we get $\alpha_E = 2.7^{+6}_{-5} \times 10^{-4}$ fm$^3$ and $L_9^r + L_{10}^r = 0.0014^{+3}_{-2}$ based on our unconstrained fit of $F_A$ and $F_V$. In addition, we use the
Minimum transverse momentum of the charged particle

\[ p_T \] 0 0.1 0.2 0.3
counts / 2.5 MeV/c
0 500 1000 1500 2000 2500 3000

\( \pi^- \text{Ni} \rightarrow \pi^- \gamma \text{Ni} \)

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

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

$\rho$ contribution from $\pi\gamma \rightarrow \pi\pi^0$

COMPASS 2009
$\pi^+\text{Ni} \rightarrow \pi^-\gamma\text{Ni}$

preliminary
Mandelstam $\{s,t\} \leftrightarrow \text{Laboratory } \{E_\gamma, \theta_\gamma\}$

for $\pi \gamma \rightarrow \pi \gamma$
M.R. Pennington in the 2\textsuperscript{nd} DAΦNE Physics Handbook, “What we learn by measuring $\gamma\gamma \rightarrow \pi\pi$ 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 $\gamma\gamma \rightarrow \pi\pi$. 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.
Primakoff production of $a_1(1260)$ vs. E272 result

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

**Mass-independent** PWA (narrow mass bins):

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

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

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

→ Physical parameters:

\[
\text{Intens}_i^\epsilon = \rho_{ii}^\epsilon,
\]

relative phase \(\Phi_{ij}^\epsilon\)

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

**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 $b_{\text{diff}} ((\text{GeV/c})^{-2})$

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

preliminary
**Isobar Model**

- **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)

**Isobar model:**

- Intermediate 2-particle decays

**Partial wave in reflectivity basis:**

$J^{PC}M^\epsilon[isobar]L$
Major intensities in $m(3\pi)$-bins (acceptance corrected)

COMPASS 2004

$\pi\text{Pb} \rightarrow \pi\pi\pi^*\text{Pb}$

$|t'| < 0.001 \text{ GeV}^2c^2$

M=0 Spin Total

M=1 Spin Total

$\alpha_2(1320)$

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

$2^{++1}$ Spin Total

COMPASS 2004

$\pi\text{Pb} \rightarrow \pi\pi\pi^*\text{Pb}$

$|t'| < 0.001 \text{ GeV}^2c^2$
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 for $t' < 10^{-3} \ (\text{GeV}/c)^2$

"Spin Totals": Sum of all contributions for given M (i.e. $z$-projection of J)

$t'$-dependent amplitudes:

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

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

$M=1$: $\sigma(t') \propto t' e^{-b_{\text{diff}}(m) t'}$ → vanishes for $t' \approx 0$
Theory: Phase $a_2$(strong+Coulomb)$-a_1$(strong)
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 $m_{3\pi}$)