Diffractive and Coulomb Dissociation of pions into three charged pions at low momentum transfer at COMPASS

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Extraction of Primakoff Signal

Partial Wave Analysis Results

Summary and Outlook
Motivation for Analysis

Meson spectrum at low momentum transfer
- Two production mechanisms
- $a_2(1320)$ resonance in detail:
  - in photon-pion process $\rightarrow \Gamma(a_2(1320) \rightarrow \pi\gamma)$
  - in diffractive (pomeron) production
  - interference effect
- More radiative couplings (heavier mesons?)
- Test of ChPT at low masses (chiral diagrams)
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Challenges and Opportunities in the light (u,d) Quark Sector

- High density of states; broad, overlapping states
- Exploit interference effects $\rightarrow$ phase motion
- Requires high statistics, complete PS coverage

$\rightarrow$ COMPASS can contribute significantly in the low mass region
COMPASS 2004 Pilot Hadron Run

Overview
- **COmmon Muon and Proton Apparatus for Structure and Spectroscopy**
- Located at CERN's SPS
- Fixed-target experiment
- Two-stage magnetic spectrometer
- Data taking since 2002

Second./Tert. SPS Beams
- Muons: $4 \cdot 10^7 \text{s}^{-1}$
- Hadrons: up to $2 \cdot 10^7 \text{s}^{-1}$
- E: 100-250 GeV

Physics Goals
- Nucleon spin structure
- Hadron spectroscopy
COMPASS 2004 Pilot Hadron Run

Experimental Setup

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Pilot Hadron Run 2004
- 190 GeV $\pi^-$ beam
- Nuclear targets (Pb)
- Tracking: Silicons for vertexing
- Trigger: Multiplicity trigger, ECAL trigger

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**Diffractive and Coulomb Production of Mesons**

- **Diffractive**: target particle remains intact
  - → low momentum transfer
  - \( I = 0 \) Reggeon t-channel exchange

- **Primakoff**: photon exchange
  - contribution at smallest momentum transfer

- **Dissociation**: beam pion is excited to a resonance \( X^- \), which subsequently decays
  - ⇒ e.g. \( \pi^- Pb \rightarrow X^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb \)

![Diffraction and Primakoff Diagram](image)

![Number of Events Graph](image)
**Diffractive and Coulomb Production of Mesons**

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  resonance \( X^- \), which subsequently decays
  ⇒ e.g. \( \pi^- \text{Pb} \rightarrow X^- \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \text{Pb} \)

- Exclusive \( 3\pi \) final state events

- COMPASS 2004 (few days of data taking):
  - \( \sim 4\,000\,000 \) \( 3\pi \) events

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### Graphical Data

- **Preliminary Data**
  - \( \pi \) \( \pi \) \( \pi \) \( \pi \) final state events
  - \( \text{COMPASS 2004} \)
  - \( \pi \text{Pb} \rightarrow \pi \pi \pi^+ \text{Pb} \)
  - \( 10^{-3} < t' < 10^{-2} \text{GeV}^2/c^2 \)

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*Stefanie Grabmüller (TUM E18) — Diffractive and Coulomb Dissociation of pions into 3 charged pions at low \( t' \) at COMPASS*
Momentum transfer to target:

\[-t = -(\vec{p}_{\text{beam}} - \vec{p}(\pi^- \pi^- \pi^+))^2 \Rightarrow t' = |t| - |t|_{\text{min}}\]

with

\[|t|_{\text{min}} = \frac{(m_{3\pi}^2 - m_\pi^2)^2}{4|\vec{p}_{\text{beam}}|^2_{\text{lab}}}\]

Diffraction pattern:
Pb nucleus acts like "black disc" in optics
Momentum transfer to target:

\[-t = -(p_{\text{beam}} - p_{(\pi^- \pi^- \pi^+)}))^2 \Rightarrow t' = |t| - |t|_{\text{min}}\]

with

\[|t|_{\text{min}} = \frac{(m_{3\pi}^2 - m_{\pi}^2)^2}{4|\vec{p}_{\text{beam}}|^2_{\text{lab}}}\]

Diffraction pattern:
Pb nucleus acts like "black disc" in optics

- "Low $t'$": $10^{-3} \text{ (GeV/c)}^2 < t' < 10^{-2} \text{ (GeV/c)}^2$ $\sim 2000000$ events
- "Primakoff region": $t' < 10^{-3} \text{ (GeV/c)}^2$ $\sim 1000000$ events
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 $m_{3\pi}$)
Basic features of the statistical subtraction

- Fit of $t'$ spectrum with sum of both exponentials for $0 < t' < 0.006 \text{ (GeV}/c)^2$ ($0.5 < m_{3\pi} < 2.5 \text{ GeV}/c^2$)
- Subtraction of “diffractive” exponent from $t'$ spectrum

Fit and subtraction in $3\pi$ mass bins:
- $b_{\text{Prim}} = 2050 \text{ (GeV}/c)^{-2}$ fixed
- $b_{\text{diff}}$ as fit parameter

Primakoff contribution
Statistical subtraction separately in 40 MeV/c^2 mass bins

Integrate Primakoff contribution of the $t'$ spectra for $t' < 10^{-3} (\text{GeV/c})^2$
Statistical subtraction separately in 40 MeV/c^2 mass bins
Integrate Primakoff contribution of the t' spectra for t' < 10^{-3} (GeV/c)^2

Events after statistical subtraction

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

Partial Wave Analysis Formalism

Isobar Model

- $J^{PC}M^\epsilon$

- 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
PWA of data with low $t'$

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

$t'$-dependent amplitudes:

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

Diffractive production:  \[ M=0: \sigma(t') \propto e^{-b_{\text{diff}}(m) t'} \]
\[ M=1: \sigma(t') \propto t' e^{-b_{\text{diff}}(m) t'} \rightarrow \text{vanishes for } t' \approx 0 \]

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Production Phase $a_2 - a_1$ for separated $t'$ regions

COMPASS 2004

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

Intensity / (40 MeV/c²)

Mass of $\pi \pi \pi^+$ System (GeV/c²)

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

t' < 0.0005 GeV²/c²

COMPASS 2004

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

Phase (degrees)

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

t' < 0.0005 GeV²/c²

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

Mass of $\pi \pi \pi^+$ System (GeV/c²)
Phase $a_2 - a_1$ in detail: $t'$ dependence

**Graph 1:**
- **Graph Title:** $1^{++}0^{+} \rho \pi S$
- **Data Source:** COMPASS 2004
- **Equation:** $\pi^- Pb \rightarrow \pi^+ \pi^- \pi^+ Pb$
- **Conditions:**
  - $t' < 0.02 \text{ GeV}^2/c^2$
  - $1.26 < m_{\pi^\pm} < 1.38 \text{ GeV}/c^2$
- **Plot Details:**
  - **Intensity (a.u.):** $10^6$
  - **Momentum Transfer $t'$ (GeV$^2$/c$^2$):** 0 to 20

**Graph 2:**
- **Graph Title:** $2^{++}1^{+} \rho \pi D$
- **Data Source:** COMPASS 2004
- **Equation:** $\pi^- Pb \rightarrow \pi^- \pi^+ \pi^+ Pb$
- **Conditions:**
  - $t' < 0.02 \text{ GeV}^2/c^2$
  - $1.26 < m_{\pi^\pm} < 1.38 \text{ GeV}/c^2$
- **Plot Details:**
  - **Intensity (a.u.):** $10^6$
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**Graph 3:**
- **Graph Title:** $\Delta \Phi (2^{++}1^{+} \rho \pi D - 1^{++}0^{+} \rho \pi S)$
- **Data Source:** COMPASS 2004
- **Equation:** $\pi^- Pb \rightarrow \pi^- \pi^+ \pi^+ Pb$
- **Conditions:**
  - $t' < 0.02 \text{ GeV}^2/c^2$
  - $1.26 < m_{\pi^\pm} < 1.38 \text{ GeV}/c^2$
- **Plot Details:**
  - **Phase (degrees):** -120 to 0
  - **Momentum Transfer $t'$ (GeV$^2$/c$^2$):** 0 to 20
Theory: Phase $a_2$(strong+Coulomb) - $a_1$(strong)

Glauber model
Plot: N. Kaiser (TU München)

⇒ indicates confirmation of interference Coulomb-interaction - strong interaction
⇒ detailed studies of the nature of resonances
COMPASS 2004 hadron run (few days) using a 190 GeV $\pi^-$ beam

$\pi^- Pb \rightarrow \pi^-\pi^-\pi^+ Pb$ at (very) low momentum transfer

Extraction of photo-produced contribution

PWA in mass bins and $t'$ bins

Production phase of $a_2(1320)$ dependent on $t'$ shows interference of contributions from Coulomb and strong interaction

Further Analysis of $3\pi$ data at low momentum transfer:

- Mass-dependent PWA:
  - Proper incorporation of Deck effect,
  - Test of chiral diagrams in threshold mass region

- Comparison with hydrogen, lead and nickel data (2009, extended spectrometer)
**π⁻π⁻π⁺ mass distribution**

Different $t'$ ranges:

![Graph showing the distribution of $\pi^-\pi^-\pi^+$ masses with different $t'$ ranges.](image)

- **COMPASS 2004**

Ranges in $t'$ (GeV$^2$/c$^2$):
- Yellow: all $t'$
- Blue: $t' < 10^{-3}$
- Red: $10^{-3} < t' < 10^{-2}$
- Green: $10^{-2} < t' < 10^{-1}$
- Cyan: $0.1 < t' < 1$
- Magenta: $t' > 1 [x5]$
**BACKUP: Partial Wave Analysis Formalism**

- **Mass-independent PWA** (narrow mass bins):
  \[
  \sigma_{\text{indep}}(\tau, m, t') = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^\epsilon f_i^\epsilon(t') \psi_i^\epsilon(\tau, m) \right|^2 \frac{\int f_i^\epsilon(t') |^2 dt' \sqrt{\int |\psi_i^\epsilon(\tau', m)|^2 d\tau'}}{\int |f_i^\epsilon(t')|^2 dt'}
  \]

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

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

- **Mass-dependent \( \chi^2 \)-fit** (not presented here):
  - \( X \) parameterized by Breit-Wigner (BW) functions
  - Background can be added
Meson Spectroscopy at COMPASS (2004)  Extraction of Primakoff Signal  Partial Wave Analysis Results  Summary and Outlook

BACKUP: Mesons and Spin-Exotic States

Constituent Quark Model
- Color-neutral $q\bar{q}$ systems
- Quantum numbers $I^G J^{PC}$
- $P = (-1)^{L+1}$  \[ C = (-1)^{L+S} \]
- $J^{PC}$ Multiplets: $0^{++}, 0^{--}, 1^{--}, 1^{++}, 1^{++}, 2^{++}, ...$
- Forbidden: $0^{+-}, 1^{++}, 2^{+-}, 3^{++}, ...$

QCD: Additional color-neutral objects
- Tetraquarks $(q\bar{q})(q\bar{q})$
- Hybrids $(q\bar{q})g$ $(\pi_1(1400), \pi_1(1600))$
- Glueballs $gg$ $(f_0(1500))$

Spin Exotic States
- $J^{PC}$ forbidden $\Rightarrow$ cannot be a $q\bar{q}$ state
- No mixing with quark model states

$\Rightarrow$ COMPASS