Light-Meson Spectroscopy at COMPASS

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Arbeitsgruppentreffen Schleching
Naïve Quark Model

Constituent quark model

- States of $u$, $d$, and $s$ (anti)quarks
- Total spin $\vec{J} = \vec{S} + \vec{L}$
- Parity $P = (-1)^{L+1}$
- Charge conjugation $C = (-1)^{L+S}$
- Certain $J^{PC}$ combinations not possible
  - $0^{--}$, $0^{+-}$, $1^{-+}$, $2^{++}$, $3^{--}$, ...
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  - $0^{--}$, $0^{+-}$, $1^{--}$, $2^{+-}$, $3^{--}$, ...
Beyond the Constituent Quark Model

QCD permits additional color-neutral configurations

- Physical mesons: linear superpositions of all allowed basis states with same $J^{PC}$
- Spin-exotic mesons: No pure $q\bar{q}$
Excited mesons appear as intermediate states

Various final states:
- $\pi^- \pi^- \pi^+$
- $\eta \pi$, $\eta' \pi$
- ...

Diffractive production in high-energy scattering
Introduction

Meson Production

Excited mesons appear as intermediate states

Various final states:

$\pi^- \pi^- \pi^+$

$\eta \pi, \eta' \pi$

...$

Diffractive production in high-energy scattering
Located at CERN (SPS)

190 GeV/c secondary $h^-$ beams:
- 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$

Various targets: $\ell H_2$, Ni, Pb, W

Two-stage magnetic spectrometer: Large acceptance over broad kinematic range
Rich spectrum of overlapping and interfering $X^-$

- Dominant states
- “Hidden” states with lower intensity

- Also structure in $\pi\pi$ subsystem
  - Successive 2-body decay via $\pi\pi$ resonance called isobar

- Also structure in angular distributions
Rich spectrum of overlapping and interfering $X^-$

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Also structure in angular distributions
Partial-Wave Analysis

Motivation

Rich spectrum of **overlapping and interfering** $X^-$
- Dominant states
- "Hidden" states with lower intensity

Also structure in $\pi\pi$ subsystem
- Successive 2-body decay via $\pi\pi$ resonance called **isobar**

Also structure in angular distributions

**1640 < m_{3\pi} < 1680\ MeV/c^2**
Rich spectrum of overlapping and interfering $X^-$
- Dominant states
- "Hidden" states with lower intensity
- Also structure in $\pi\pi$ subsystem
  - Successive 2-body decay via $\pi\pi$ resonance called isobar
- Also structure in angular distributions
Partial wave \( a = J^{PC} M^\pi \xi \pi L \) at fixed mass \( m_{3\pi} \)

- Calculate 5D decay phase-space distribution of final-state particles

- \( \psi_a(\tau) \) describes distribution of wave \( a \) in decay phase-space variables \( \tau \)

- Total intensity distribution: Coherent sum of partial-wave amplitudes

\[
I(\tau) = \left| \sum_{a} T_a \psi_a(\tau) \right|^2
\]

- Perform maximum-likelihood fit in cells of \( m_{3\pi} \) and \( t' \)

- Decompose data into partial waves

- Extract \( m_{3\pi} \) and \( t' \) dependence of partial-wave amplitudes
Partial-Wave Analysis
Isobar Model

[Adolph et al., PRD 95, 032004 (2017)]

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- Extract \( m_{3\pi} \) and \( t' \) dependence of partial-wave amplitudes
Partial wave $a = J^{PC} M^\varepsilon \xi \pi L$ at fixed mass $m_{3\pi}$

- Calculate 5D decay phase-space distribution of final-state particles

- $\psi_a(\tau)$ describes distribution of wave $a$ in decay phase-space variables $\tau$

- Total intensity distribution: Coherent sum of partial-wave amplitudes

\[ \mathcal{I}(\tau) = \left| \sum_a T_a \psi_a(\tau) \right|^2 \]

- Perform maximum-likelihood fit in cells of $m_{3\pi}$ and $t'$
  - Decompose data into partial waves
  - Extract $m_{3\pi}$ and $t'$ dependence of partial-wave amplitudes
Partial-Wave Analysis
Resonance-Model Fit

Data

(1) Partial-Wave Decomposition

Partial Waves
Intensities and relative phases of the partial waves

Resonance Parameters
Masses and widths of the meson resonances
Partial-Wave Analysis

Resonance-Model Fit

Data

(I) Partial-Wave Decomposition

Partial Waves
Intensities and relative phases of the partial waves

(II) Resonance-Model Fit

Resonance Parameters
Masses and widths of the meson resonances
Modeling $m_{3\pi}$ dependence

- Parameterize $m_{3\pi}$ dependence of partial-wave amplitudes (intensity & phase)

$$T_\alpha(m_{3\pi}, t') = \sum_{k \in \text{Comp}_\alpha} C^k_\alpha(t') \cdot D^k(m_{3\pi}, t'; \zeta_k)$$

- Resonances: Breit-Wigner amplitude
- Non-resonant terms: Phenomenological parameterization
Partial-Wave Analysis
Resonance-Model Fit

Modeling $m_{3\pi}$ dependence

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- Resonances: Breit-Wigner amplitude
- Non-resonant terms: Phenomenological parameterization

Graph showing the model fit for $0^{-+} f_0(980) \pi S$ with $0.100 < t' < 1.000$ (GeV/c)^2.

Intensity / (20 MeV/c^2^) vs $m_{3\pi}$ [GeV/c^2].
Partial-Wave Analysis
Resonance-Model Fit

Modeling $m_{3\pi}$ dependence

- Parameterize $m_{3\pi}$ dependence of partial-wave amplitudes (intensity & phase)
  $$\mathcal{T}_\alpha(m_{3\pi}, t') = \sum_{k \in \text{Comp}_\alpha} C^k_\alpha(t') \cdot D^k(m_{3\pi}, t'; \zeta_k)$$

- Resonances: Breit-Wigner amplitude
- Non-resonant terms: Phenomenological parameterization
\[ J^{PC} = 1^{--} \text{ State} \]

- \( 1^{-+} \): spin-exotic \( \pi_1 \)-like quantum numbers
  - Forbidden quantum numbers for \( q \overline{q} \) system (non-rel.)
  - Lattice-QCD: lightest hybrid predicted with \( 1^{--} \) quantum numbers
\( J^{PC} = 1^{-+} \) State

Resonance-Model Fit

\[
\Gamma^{1+} \rho(770) \pi P
\]

0.100 < \( t' \) < 1.000 (GeV/c)^2

Model curve
Resonances
Nonres. comp.

\( \pi_1(1600) \)

- Large non-resonant contribution in spin-exotic 1^{-+} wave, but ...
- Strong modulation with \( t' \) is exploited in \( t' \)-resolved analysis
- No description of data at high \( t' \) without Breit-Wigner component
\( J^{PC} = 1^{-+} \) State

Resonance-Model Fit

\[ \Gamma^{+1} \rho(770) \pi P \]

\( 0.100 < t' < 0.113 \) (GeV/c)²

Model curve
Resonances
Nonres. comp.

\( 0.724 < t' < 1.000 \) (GeV/c)²

Model curve
Resonances
Nonres. comp.

\( \pi_1(1600) \)

- Large non-resonant contribution in spin-exotic \( 1^{-+} \) wave, but ...

- **Strong modulation with \( t' \) is exploited in \( t' \)-resolved analysis**

- No description of data at high \( t' \) without Breit-Wigner component
\[ J^{PC} = 1^{-+} \] State

Resonance-Model Fit

\[ [1^{-+} \rho(770) \pi P] - [1^{++} \rho(770) \pi S] \]

\[ 0.724 < t' < 1.000 \text{ (GeV/c)}^2 \]

\[ \Delta \phi \text{ [deg]} \]

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

\[ 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \]

\[ \times 10^3 \]

\[ 1 \]

\[ 0.724 < t' < 1.000 \text{ (GeV/c)}^2 \]

- Model curve
- Resonances
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\[ \pi_1(1600) \]

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Freed-Isobar Analysis

- Allows to study $\pi^- \pi^+$ isobar amplitude
  - for specific $j^{pc}$ of $\pi^- \pi^+$ isobar system
  - for specific $J^{PC}$ of $\pi^- \pi^- \pi^+$ system
  - as a function of $m_{3\pi}$
- Study many different isobar amplitudes simultaneously
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Freed-Isobar Analysis

\( J^{PC} = 1^{-+} \) Wave with freed \( J^{PC} = 1^{-+} \) Isobar Amplitude

\[ 1580 < m_{3\pi} < 1620 \text{ MeV} \]

- \( m_{\pi^- \pi^+} \) spectrum shows good agreement with \( \rho(770) \) Breit-Wigner
- Extract \( m_{\pi^- \pi^+} \) dependence of complex-valued amplitude
- Study \( \pi^- \pi^+ \) amplitude as a function of \( m_{3\pi} \)
- Shape of \( m_{3\pi} \) spectrum is in fair agreement with fixed-isobar analysis
  \[ \pi_1(1600) \text{ signal at about 1.6 GeV/c}^2 \text{ robust} \]

S. Wallner

Light-Meson Spectroscopy at COMPASS
Freed-Isobar Analysis

\[ J^{PC} = 1^{-+} \text{ Wave with freed } j^{PC} = 1^{--} \text{ Isobar Amplitude} \]

- \( m_{\pi^-\pi^+} \) spectrum shows good agreement with \( \rho(770) \) Breit-Wigner
- Extract \( m_{\pi^-\pi^+} \) dependence of complex-valued amplitude
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\( J^{PC} = 1^{--} \) Wave with freed \( J^{PC} = 1^{--} \) Isobar Amplitude

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- Extract \( m_{\pi^- \pi^+} \) dependence of complex-valued amplitude
- Study \( \pi^- \pi^+ \) amplitude as a function of \( m_{3\pi} \)
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  - \( \pi_1(1600) \) signal at about 1.6 GeV/c\(^2\) robust
Golden channels for spin-exotic states

Partial-wave amplitudes from COMPASS [PLB 740 (2015) 303]

Analytic and unitary coupled-channel model based on S-matrix principles
  - Resonances are poles in the amplitude
Data requires single pole in amplitude of $1^{-+}$ waves

Consistent with Breit-Wigner mass and width from $\pi^- \pi^- \pi^+$
JPAC Coupled-Channel Analysis of $\eta \pi$ and $\eta' \pi$

[Rodas et al. [JPAC], PRL 122 (2019) 042002]

**$\eta \pi$**

- Data requires single pole in amplitude of $1^{-+}$ waves
- Consistent with Breit-Wigner mass and width from $\pi^- \pi^- \pi^+$

**$\pi^- \pi^- \pi^+$**

- $0.449 < t' < 0.724$ (GeV/c)$^2$
- Model curve
- Resonances
- Nonres. comp.
Intensity of $J^{PC} = 1^{-+}$ Wave in $\eta^{(i)}\pi$ and $\pi\pi\pi$
Freed-Isobar Analysis: Study $\pi\pi$ in 3–Body Environment

 [$\pi\pi$]$_S$ Wave from $J^{PC} = 1^{++}$ and $J^{PC} = 0^{--}$

- Study $\pi^- \pi^+$ system with $j^{pc} = 0^{++}$
  - At different $m_{3\pi}$
  - For different $J^{PC}$ of the $\pi^- \pi^- \pi^+$ system
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$[\pi\pi]_S$ Wave from $J^{PC} = 1^{++}$ and $J^{PC} = 0^{--}$

- Study $\pi^-\pi^+$ system with $j^{PC} = 0^{++}$
  - At different $m_{3\pi}$
  - For different $J^{PC}$ of the $\pi^-\pi^-\pi^+$ system

$1^{++0^+} [\pi\pi]_{0^{++}} \pi P$

$0.100 < t' < 0.141 \text{ (GeV/c)}^2$

$1.38 < m_{3\pi} < 1.42 \text{ GeV/c}^2$

$\text{Int} \times 10^6

\text{Intensity (GeV/c}^2\text{)}^{-1}$

$m_{\pi^-\pi^+} [\text{GeV/c}^2]$
Freed-Isobar Analysis: Study $\pi\pi$ in 3–Body Environment

$1^{++}0^+$ $[\pi\pi]_{0^{++}}\pi P$

$0.100 < t' < 0.141$ (GeV/c)$^2$

$1.50 < m_{3\pi} < 1.54$ GeV/c$^2$

$[\pi\pi]_S$ Wave from $J^{PC} = 1^{++}$ and $J^{PC} = 0^{--}$

Study $\pi^-\pi^+$ system with $j^{pc} = 0^{++}$

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Freed-Isobar Analysis: Study $\pi\pi$ in 3-Body Environment

[S. Wallner, Light-Meson Spectroscopy at COMPASS 17/17]

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